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Proceedings of the Technical Cooperative Program Workshop: Inflatable Restraints in Aviation

Edited by John S. Crowley and Clifton L. Dalgard

Aircrew Protection Division

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Aviation accidents frequently result in death or injury--occupant flail with resultant head injury is the leading cause of fatality and serious injury in Army helicopter accidents. Inflatable restraints are a proven safety technology in the automotive world, and airbags are being developed for Army helicopters as well. Other applications in transport safety such as inflatable motorcycle helmet collars and inflatable restraint harnesses may be useful in aviation--research is underway in exciting novel areas.

There are many questions to be answered before airbags and similar systems can be fielded in aircraft. Hot issues range from the unique characteristics of a helicopter crash pulse to the effects of unintended airbag deployment on injury and aircraft control. Tools useful in this research include computer modeling, anthropometric test devices, cadaver research, and flight simulation/testing.

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THE TECHNICAL COOPERATION PROGRAM

SUBCOMMITTEE ON NON-ATOMIC MILITARY RESEARCH AND DEVELOPMENT

TTCP TECHNICAL REPORT

Proceedings of the Workshop: Inflatable Restraints in Aviation

May 2000

TTCP/HUM/00/009

FOREWORD

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Thanks are due to SPC Clifton Dalgard for his assistance with the organization of the workshop and these proceedings. Also, special funding enabled by LTC Karl Friedl, of the U.S. Army Medical Research and Materiel Command, facilitated a successful meeting.

It is our pleasure to publish herein the collected workshop papers.

John S. Crowley
COL, MC, U.S. Army
Editor
U.S. Army Member, TP-7

John A. Powell
COL, MC, U.S. Army
Commander
U.S. Army Aeromedical Research Laboratory

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Occupant Restraint in U.S. Army Aviation: An Historical and Personal Perspective

Dennis F. Shanahan, M.D., M.P.H.
Colonel, U.S. Army (Retired)

Vice President, ARCCA, Incorporated
2288 Second Street Pike
Penns Park, PA 18943-0078

ABSTRACT

Proper restraint of occupants in crashes of both air and land vehicles is one of the most critical factors in occupant survival in all but the most minor impacts. Restraint systems serve multiple functions including prevention of ejection, reduction of upper torso and head flailing, and force distribution. As demonstrated in the Black Hawk and Apache helicopters, proper occupant restraint is best accomplished through an integrated crashworthiness system design.

In spite of highly optimized and integrated seat and belt restraint designs, serious injury is still occurring in U.S. Army helicopter crashes because of excessive flailing of the head, upper torso and extremities. Although the use of inflatable restraints in aircraft requires overcoming many complex technical challenges, it remains the most practical approach for solving the problem of flailing. This paper will provide a historical review and personal perspective on the challenges of occupant restraint, discuss inflatable restraints in automotive applications, provide a rationale for utilizing inflatable restraints in aviation, and discuss the essential design features required to optimize performance of inflatable restraints in aviation applications

BACKGROUND

Proper restraint of occupants in crashes of both air and land vehicles is one of the most critical factors in occupant survival in all but the most minor crashes. Proper restraint in concert with maintenance of a protective shell, energy absorbing structure and crew seats, "delethalization" of the interior, and control of post crash hazards such as fire form the major design factors that must be considered in maximizing survival in crashes. When all these factors are considered and integrated into a coherent design, amazing levels of survivability can be achieved. The UH-60 Black Hawk and AH-64 Apache helicopters provide excellent examples of systems where all these factors were considered and applied to the final design. Research and field experience have shown that when all these factors are addressed, occupants have survived impacts well in excess of 40g without serious injury.[19] In fact, event data recorders installed in "Indy" cars have recently recorded accelerations in excess of 100g in crashes where the drivers escaped without

serious injury.[17] These new data suggest that man may not be as delicate as previously thought and, if provided with state-of-the-art protective systems, may be able to withstand crash forces over twice the level currently believed possible.

In considering the issue of "proper" restraint, it is interesting that the definition of proper has evolved considerably over this past century as understanding of crash survivability issues has increased. Lap belt restraints were originally introduced in the early days of aviation to keep the pilot in the airplane during extreme maneuvers rather than to protect him in a crash.[15, 16] Indeed, many considered belts dangerous in crashes since they prevented the pilot from being ejected free of the wreckage during the crash. In the course of performing crash investigations today, one still occasionally hears this sentiment expressed although the evidence is overwhelmingly in favor of the benefits of proper restraint.

Shoulder belt restraints were introduced into aircraft some time later to prevent the upper torso and head from flailing into the instrument panel in a crash. It appears that these first shoulder belt systems in aviation were of the 4-point configuration or having two shoulder straps and the two lap belt straps. In automotive applications, the first shoulder belts were apparently of the "sash" or 2-point configuration.[2] The standard 3-point automobile system widely used today was developed by Neils Bohlin of Volvo in order to improve the relatively poor restraint offered by the sash belt systems. In aviation applications, a fifth strap, the tie-down strap or crotch strap, was added to the 4-point system to help prevent a condition known as "submarining" which occurs when the lap belt rides up over the iliac crests of the occupant when the shoulder belts are loaded. Since that time, belt restraints have maintained essentially this same configuration but with the addition of many peripheral improvements including introduction of inertia reels, more convenient and easier to use single-action-to-release buckles, and improvements in webbing strength and elongation characteristics. Pretensioners and web clamps have also been used in automotive applications.

The net result is that belt restraint systems used in military aviation today have become extremely efficient and relatively convenient to use. Unfortunately, even the best systems allow considerable head and upper torso motion during impact loading. As an example, impact tests were performed in the Black Hawk crew seat in the early 1980's to verify the load limit for the energy absorbers used in the seat.[4] Under high vertical load crash conditions, the cadaver surrogates used in the tests were noted to have considerable flailing of their heads and upper torsos in spite of using a pre-locked and tightened restraint system (Figure 1). In some of the tests the heads flexed forward and downward sufficiently that it appeared they would have struck the cyclic if one were installed on the test fixture. The presence of head and upper torso flailing during crashes in spite of the use of a well-designed belt restraint system has been verified in field crash investigations as will be discussed below.

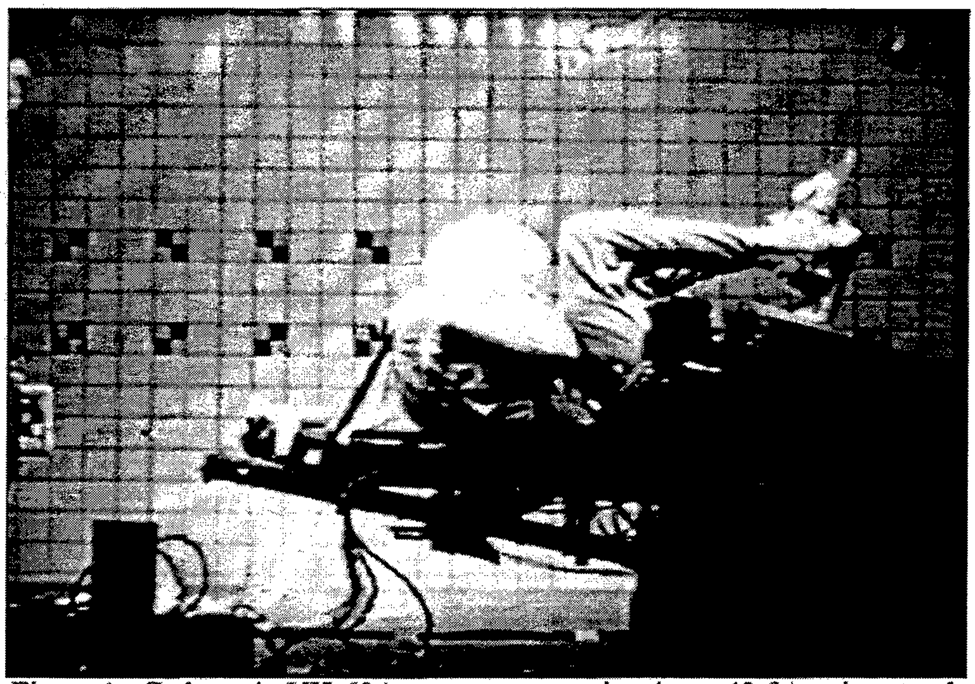


Figure 1. Cadaver in UH-60A crew seat experiencing a 42 ft/sec input pulse. Note degree of flexion of head.

The U.S. Army Role in Crashworthiness Development

The U.S. Army has a long and distinguished history of being the leader in aircraft crashworthiness research and development. Most of the pioneering work in the field began in the 1960's when the Army funded research and development programs in crash resistant fuel tank development, seat and restraint system design, and structural crashworthiness. The Aviation Crash Injury Research Group (AVCIR) of the Flight Safety Foundation did much of this work, culminating in the publication of the Crash Survival Design Guide.[19] The Design Guide was a compendium of knowledge on occupant protection, and it provided a blueprint for the design of crashworthy aircraft. This important document has undergone multiple revisions under the auspices of the Aviation Applied Technology Directorate (AATD) of the Aviation and Troop Command since its initial publication.

The Vietnam War provided the impetus to implement many of the concepts developed by this pioneering research in crashworthiness. First, the Vietnam War had solidified the air mobility concept and confirmed the role of the helicopter for the Army of the future. Second, many of the decision makers had first-hand experience seeing the effects of helicopter crashes and the unnecessary deaths caused by a lack of crashworthiness, particularly from fuel-fed post crash fires.[5] Consequently, after 1970 all newly manufactured Army helicopters were equipped with a crashworthy fuel system (CWFS) and an extensive retrofit program was begun to equip most Army helicopters with CWFS by 1976. This change proved to be the single most effective improvement in Army helicopter crash survivability yet implemented. Studies showed that thermal burns

caused 40 percent of deaths in survivable crashes of helicopters without crashworthy fuel systems.[14] By 1989, a follow on study of injuries in Army helicopter crashes was only able to identify one death due to thermal burns in a crashworthy fuel system equipped helicopter involved in a survivable crash.[10]

A survivable crash is defined as one in which the forces transmitted to the occupant through the seat and restraint system do not exceed the limits of human tolerance and in which the occupied cabin/cockpit space is not substantially compromised. Note that this definition is based upon aircraft and crash kinematic factors and is independent of the actual outcome for any occupants. Consequently, there may be survivable crashes in which all occupants are fatally injured or non-survivable crashes where all occupants survive. It is the survivable accidents where occupants are seriously or fatally injured and the non-survivable crashes where occupants survive that provide the best information regarding performance limits of crash protective items or systems.

Coincidental with the introduction of crashworthy fuel systems was the Army's Utility Tactical Transport Aircraft System (UTTAS) and Advanced Attack Helicopter (AAH) development programs. Both of these programs specified crashworthiness requirements for the developmental helicopters based upon the specifications recommended in the Crash Survival Design Guide.[3, 6] The UH-60 Black Hawk and the AH-64 Apache were the products of these development programs, becoming the first helicopters to be designed and fielded with crashworthiness as a primary design objective. The crash experience of these helicopters has proven that an integrated systems approach to crash survivability can be highly effective. An analysis of Black Hawk crashes has shown that the Black Hawk provides protection from fatal injury for vertical impacts exceeding 60 ft/s (18.3m/s), whereas its predecessor, the UH-1, provides protection for vertical impacts only up to approximately 40 ft/s (12.2 m/s).[8, 9] This difference represents a 125 percent increase in vertical energy management capability for the Black Hawk over the UH-1 (Figure 2).

As significant as this improvement is, there are as many or even more injury producing crashes of the Black Hawk and Apache as any of their predecessors. Why is this occurring? The answer is really quite straightforward—these helicopters tend to crash at much higher vertical and horizontal velocities than their predecessors.[7, 11, 13] This is related to their higher operational speeds, relatively low inertia rotor systems and high disk loading. They are also flying much riskier mission profiles than their predecessors. The net result is that these newer generation helicopters have proven that they need substantially better crashworthiness than their predecessors because of their vastly improved operational capabilities and inherently riskier mission profiles.

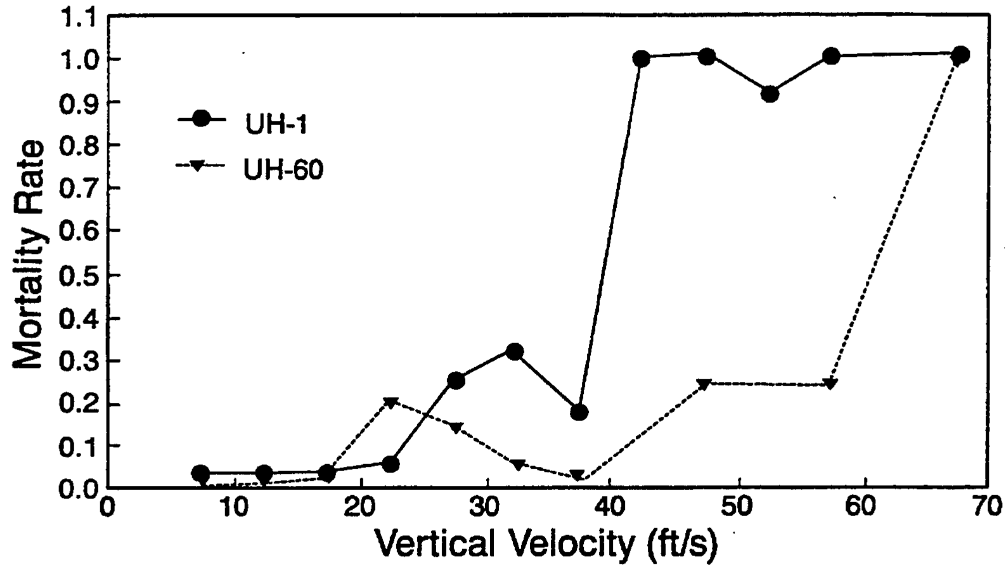


Figure 2. Mortality rate versus impact vertical velocity for UH-1 and UH-60.

Crash Injury Studies

In order to understand how injuries were occurring in potentially survivable crashes, several extensive studies of crash injury were undertaken in the late 1980's and early 1990's.[7, 10, 13] The overriding philosophy behind these studies was a firm conviction that further progress in occupant protection in Army helicopters could not be effectively achieved without a thorough understanding of the prevalent injury mechanisms occurring in crashes and particularly in crashes of "crashworthy" helicopters. Such studies not only identify and quantify prevailing injury mechanisms, they also provide the basis to prioritize potential remedial measures based on costs. This becomes particularly important in the stringent fiscal environment of today.

In general, all mechanical injury arising from aircraft crashes may be classified into either acceleration injury (inertial injury) or contact injury. In a strict sense, both forms of injury arise from application of force to the body through an area of contact with an accelerating surface. In the case of acceleration injury, the application is more distributed so that the site of force application usually does not receive a significant injury. The site of injury is distant from the area of application and is due to the body's inertial response to the acceleration experienced by the aircraft. An example of an acceleration injury is rupture of the aorta in a high sink rate crash.

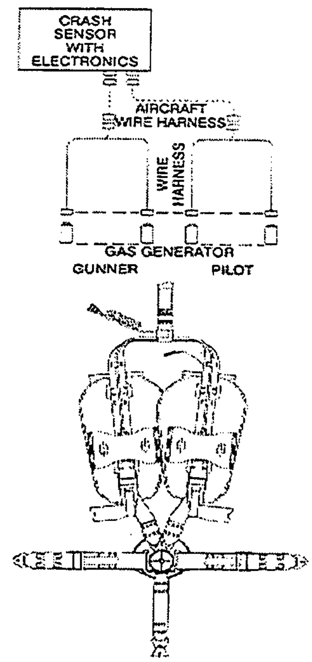
Contact injury occurs when a localized portion of the body comes into a contact with a surface in such a manner that injury occurs at the site of contact. Relative motion between the body part and the contacting surface is required, resulting from movement of the body, movement of the impacting surface or a combination of both. An example of this type of injury is a depressed skull fracture resulting from the head striking a bulkhead.

Among the major findings of epidemiological studies of crash injury was that the new generation crashworthy helicopters were providing a substantial increase in protection to occupants in crashes over their predecessors considering the higher impact velocities of the new generation helicopters. Secondly, regardless of the helicopter type, approximately 43 percent of occupants received fatal or disabling injuries in survivable crashes. An analysis of these injuries showed that the majority was due to the "secondary impact" with the aircraft interior. These impacts were caused by collapse of structure into occupied areas, by inadequate restraint of the occupants, which allowed them to flail into structure, or by a combination of both mechanisms. The most frequently injured body regions in survivable crashes were the head (28%) and extremities (43%). Acceleration or inertial injuries occurred relatively infrequently. In fact, Shanahan estimated that contact injury exceeded acceleration injury by a ratio of five to one.[10]

The overwhelming conclusion reached by these studies was that the major problem causing injury in survivable crashes of all types of Army helicopters is contact injury caused by flailing of occupants into structure. Collapse of structure into victims did not play a major role in these injuries since, by definition, these survivable crashes could not have involved significant deformation of structure into occupied areas. Therefore, the major thrust of Army crashworthiness enhancement programs should be directed at reducing occupant flailing during crashes.

Reducing Flail Injury

In theory, there are a number of basic approaches available to prevent contact injuries in crashes. The first and most direct approach is to prevent the contact through improved restraint system design or improved structural crashworthiness. The second is doing what is frequently referred to as "delethalizing the cockpit". This process consists of moving potentially injurious objects out of the strike zone of the body, padding potentially injurious surfaces or making them frangible so that any contact that occurs during a crash will not be injurious. A third option is to provide the occupant with personal protective equipment



IBAHRS system components.

IBAHRS deployed.

Figure 3. Inflatable Body and Head Restraint System (Simula, Inc.)

such as a flight helmet to mitigate the injurious effect of contact with otherwise injurious objects. In practice all these strategies are employed in Army helicopters because they all have technical and practical limitations. This is particularly true for the latter two strategies. Delethalization is practically limited by cockpit size, which requires bulkheads, doors, armor, and other structural items to be in close proximity to occupants. Furthermore, controls and instruments, by their very nature, must remain within the strike zone of pilots. Padding and making these objects frangible has also not been shown to be effective or practical. Helmets have been very effective in reducing head injury, but seem to have reached a practical limit since 28 percent of injuries in survivable crashes are to the head in spite of universal use of flight helmets by cockpit crewmembers.[10] Consequently, the most viable option for decreasing contact injuries in survivable crashes is to improve occupant restraint.

In considering this problem, a number of potential solutions have been considered. One is to find means of improving belt restraint systems by adding additional belts, changing the geometry of belts, enhancing the effectiveness of inertia reels or adding webbing clamps. Most of these options have been tried and either failed to meet pilot acceptance (addition of chest belts), were too cumbersome to allow for single-point release, or they failed to provide sufficient additional restraint to prevent flail injuries. This led researchers to consider several forms of inflatable restraint systems.

The Inflatable Body and Head Restraint System (IBAHRS) was developed, primarily by the Navy, to prevent flail of the head and chest.[7] Basically, it consisted of an airbag integrated into a 5-point belt restraint system that would activate when an aircraft

mounted crash sensor detected a crash (Figure 3). The inflatable bags located in the shoulder belt would provide several functions. They would ensure lock-up of the inertial reel and provide pre-tensioning of the belts which would help reduce upper torso flail. The extension of the bag under the chin would provide support to the head and prevent flailing motions of the head and neck. Impact testing of this system has proven it to be very effective in reducing head and torso flail, although it did not significantly reduce flail of the extremities. It had the advantage that it could be integrated into existing cockpits with minimal modifications to the airframe and inadvertent inflation of the system was minimally disruptive of continued operation of the aircraft. Its downside is that it will not provide the same degree of protection as a full air bag system. Although IBAHRS is essentially a fully developed and tested system, it has not been integrated into any airframe.

The other inflatable system considered was a full air bag system patterned after the systems currently used in automotive applications. In 1988 AATD began a research program to explore the feasibility of integrating air bags into Army helicopter cockpits. Known as the Cockpit Air Bag System (CABS) program, this program conducted under contract to Simula, Incorporated, proved that it was feasible to integrate air bags into attack helicopter cockpits and that the technology for doing so existed (Figure 4). The advantages of integrated supplemental air bags include convenience and comfort to the cockpit aircrew. It is a passive system that does not involve any additional constraint on their activities. An air bag system not only provides restraint, it also provides padding by imposing an energy absorbing surface between the occupant and potentially injurious objects. It provides restraint of the extremities as well as the head and torso. On the downside are potential problems with inadvertent inflation, contact with the air bag causing injury, egress obstruction, and the considerable technical problems involved in tailoring an air bag system to aviation and integrating the system into a specific cockpit.

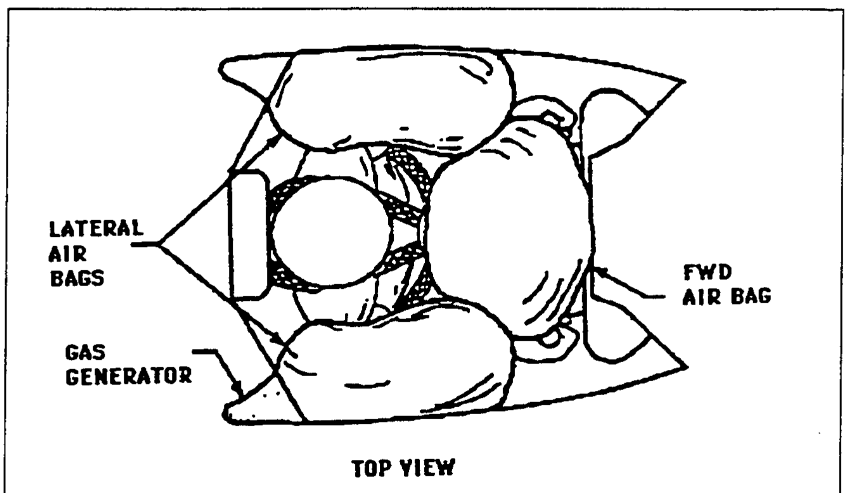


Figure 4. Original CABS configuration for attack helicopter.

Concurrent with this effort, the U.S. Army Aeromedical Research Laboratory (USAARL) in conjunction with the Naval Biodymanics Laboratory (NBDL), performed exploratory dynamic impact testing to determine the potential for cockpit air bags to reduce head

injury in helicopter crashes. In this program, mock-ups of the front cockpit of the AH-1 and AH-64 attack helicopters were used in conjunction with off-the-shelf Honda automobile air bags. This testing with air bags showed significant reduction in head injury parameters for the Hybrid III dummies used in the testing (Table I).[1]

Test group and improvement due to airbag	Head peak (G)	Head injury criterion	Acceleration pitch swing (rad/s^2)	Velocity pitch swing (rad/s)
Cobra TSU tests$^{(1)}$ without airbag	141	871	12850	70.5
Cobra TSU tests$^{(2)}$ with airbag	47.8	170	3328	22.5
Improvement	66%	80%	74%	68%
Apache ORT tests$^{(3)}$ without airbag	59.9	93	9920	40.5
Apache ORT test$^{(4)}$ with airbag	13.8	31	1300	6.3
Improvement	77%	67%	87%	84%

Table I. Results of NBDL sled tests using Honda air bag system.

In 1993, at the request of U.S. Army Program Executive Officer for Aviation, a cost-effectiveness study for the installation of air bag systems in various Army helicopters was conducted by the USAARL.[12] This study evaluated all Class A and B crashes of Army helicopters over a 9-year period for injuries to cockpit occupants. The cost of these injuries was estimated, as was the number of injuries which could have been prevented or mitigated by air bags. The results using rather conservative criteria showed an overall reduction in aviator fatalities of 23 percent and a reduction of all injuries of 39 percent for air bag equipped helicopters (Table II). In some airframes the overall injury reduction was estimated in excess of 50 percent. The overall annual cost reduction to the Army was estimated at $4.3 million. This cost reduction estimate was extremely conservative both because of the use of very stringent injury criteria but also because cost estimates in the report were based on Department of Defense criteria, which are considerably lower than actuarial figures used by insurance companies. The figures also fail to reflect the pain, disability and disruption of lifestyle that many crewmembers experience as a result of these injuries. There was also considerable variation in injury prevention among different helicopters with the largest cost reductions predicted in the UH-1, OH-58, and UH-60.

Degree of injury	Helicopter type						
	AH-1	AH-64	CH-47	OH-58	UH-1	UH-60	Total
Fatal	8 33.3%	1 14.3%	1 14.3%	9 29.0%	7 20.0%	4 16.7%	30 23.4%
Permanent total	.	.	.	1 100%	1 100%	1 100%	3 100%
Permanent partial	0	1 50.0%	.	2 20.0%	3 60.0%	2 40.0%	8 34.8%
Workdays away	10 76.9%	10 62.5%	2 100%	16 39.0%	25 51.0%	11 47.8%	74 51.4%
Workdays restricted	1 50.0%	3 75.0%	1 25.0%	2 18.2%	6 60.0%	1 100%	14 43.8%
Total	19 47.5%	15 51.7%	4 30.8%	30 31.9%	42 42.0%	19 35.2%	129 39.1%

Table II. Estimated reduction in injuries if CABS were installed.

Cockpit Air Bags

A careful consideration of the above issues inevitably leads one to the conclusion that the single best option to reduce contact injury in Army helicopter crashes in terms of cost, weight, convenience, comfort and reliability is to improve occupant restraint through the use of integrated air bag supplemental restraint systems. Although the addition of air bags to Army cockpits will not be a panacea, they will eliminate approximately 30 to 50 percent of all injuries for any particular airframe. The proportion of injuries prevented in survivable crashes will be considerably higher.

At the beginning of the CABS program in the late 1980's, most of us working on the program rather naively believed that putting air bags into a helicopter would be a relatively straightforward process of adapting automotive technology to a helicopter cockpit. After all, we had shown the effectiveness of air bags in horizontal accelerator tests by using a system out of an automobile without making any modifications! Unfortunately, as with most research and development, the devil proved to be in the details. As it turned out, very little of the technology in automotive air bag systems was directly transferable to the Army helicopter crash environment. For instance, the bag material used in automobile applications did not meet Army flammability standards. This required a search for an appropriate material that would meet the flammability requirements yet be able to be folded into a tight package, remain folded and compressed without deterioration for years, and still remain intact when inflated under considerable pressure when required. Most automotive inflators used sodium azide, which was judged to be too toxic for Army applications. This problem required development of a new propellant and inflator system. Automobile crash sensors were primarily electromechanical and uniaxial, characteristics which did not meet the needs for the three dimensional environment of helicopter crashes. This required development of new sensor technology including the algorithms necessary for determining appropriate firing parameters under helicopter crash conditions. Because of these and other technical problems, the development of a basic air bag system has turned out to be much longer and costlier than originally anticipated. This effort continues today.

Once these general developmental issues are resolved there remains the very difficult problem of adapting the system to a particular cockpit. This includes determining how many bags are required to provide protection and then finding suitable mounting locations that do not interfere with the current cockpit layout. The mounting locations also must have sufficient strength to react the forces of an occupant loading into the air bag. Once location is determined the shape and folding pattern of the bags must be established to provide suitable deployment characteristics of each bag within the cockpit. Other considerations include determining a mounting location for the crash sensor and integrating the electronics of the system into the helicopter system. Finally, there are overriding safety issues—avoiding inadvertent inflation, ensuring an inadvertent inflation does not result in a crash, dealing with issues of an out-of-position occupant being injured by a deploying air bag, and ensuring that air bags do not interfere with egress particularly in crashes in water.

Essential Characteristics of a Helicopter CABS

There are numerous other considerations in developing an effective air bag system for a particular platform that are beyond the scope of this paper. Suffice it to say that I am confident the technological problems can be surmounted given the appropriate resources and time. Nevertheless, as development of a cockpit air bag system progresses, there are a number of features or characteristics of the system that I consider essential and should not be eliminated or ignored as the result of actions directed at cost containment.

1. Programmability of the crash sensor

Unlike the automobile industry, we do not have the luxury of being able to run multiple full-scale crash tests on helicopters before, or even after, they are fielded. At best, a number of components, such as landing gear and seats, are dynamically tested to ensure compliance with specifications. In the absence of crash test data, crash investigators must estimate crash dynamics for any particular crash based on comparisons to component test data or estimates of velocity derived from witnesses or cockpit instruments. Both of these methods are highly subjective and fraught with error. Consequently, the crash parameters assembled for any particular helicopter are estimates without clear knowledge of the degree of error contained in those estimates.

The fire/no-fire thresholds programmed into the crash sensor for the cockpit air bag system must be based on estimates of the crash dynamics experienced by each platform in which the system is integrated. This means that there is a high probability that the algorithm programmed into the crash sensor will not be optimized for the platform in which it is installed. Crash experience with these systems will undoubtedly indicate a need to "fine-tune" the algorithms after the systems are fielded. Without a capability to reprogram the crash sensor algorithm after the system is fielded, it will be necessary to replace the sensors to make any desired changes to the algorithm. This will be a very expensive undertaking, and it is unlikely that in the current fiscal environment such funds will be available. Therefore, considering the high probability of the need to change the

algorithm for the crash sensors based on future crash experience, it is essential that the crash sensors have the capability of being reprogrammed in the field through a relatively simple interface.

2. Downloadable memory

The crash sensors for the Cockpit Air Bag System will contain accelerometers to detect a crash event. The data that the accelerometers generate are not only essential for determining whether to fire the inflators for the air bag system, but they are also essential for increasing our understanding of crash kinematics. Accurate crash data gleaned from these air bag sensors will vastly improve our knowledge of the crash environment in a number of ways. These data will help improve understanding of human tolerance to crash accelerations by providing actual crash force measurements instead of back-calculated estimates. They will provide means of judging whether energy-absorbing systems in an airframe such as stroking landing gear and energy attenuating seats are optimized for the crash conditions experienced by the airframe. They will provide a basis for assessing the adequacy of current crashworthiness specifications. Finally, they will provide the information required to optimize the crash algorithms utilized in the crash sensors for each CABS.

Consequently, it is essential to provide the CABS crash sensors with non-volatile memory capable of storing accelerometer data for a period of time before, during and after the crash pulse. These data must be readily accessible by crash investigators either in the field or through a relatively simple laboratory procedure. Considering the state of the art, this capability should not appreciably increase the cost of the crash sensor, particularly considering its value to crash investigations and to future crashworthiness design. This concept has already been proven in automotive applications. General Motors has been installing event recorders in many of their automobiles for several years and Ford Motor Corporation reports that all their vehicles will have a limited version on all their 1999 models.[18] One of the functions of these event recorders is to store vehicle dynamic data gleaned, in part, from air bag crash sensors. The data is downloaded after a crash through a simple hand-held computer interface.

3. Inflation threshold consistent with the crash environment

The purpose of the CABS is to provide **supplemental** restraint to the generally good restraint already available in Army helicopters. It is not necessary to deploy the air bag system in low velocity impacts since the current belt restraint systems are adequate to protect occupants at these force levels. In other words, the system should be designed for the fully restrained occupant. This minimizes the probability of inadvertent inflation caused by non-crash events such as hard landings, weapons firing or g-loads imposed by evasive maneuvering or severe weather conditions. Another advantage is that the system is more likely to activate for the major impact in a multiple impact crash event, thus preserving the full capability of the system for when it is most needed. A relatively high threshold also reduces the total number of inflations experienced and, thereby, reduces the opportunity for potentially injurious occupant/air bag interactions. The downside to

this concept is that the design of the air bag system must allow for occupants to be relatively out of position at the time of air bag inflation. Therefore, the requirement to delay inflation must be balanced with parameters such as air bag size, location of modules, air bag shape and deployment pattern, and aggressivity of inflation. Finding the right compromise is an extremely difficult technical task, and may require the use of dual inflators, staged inflation, occupant position sensing, or other concepts similar to those now being developed for automotive air bags to solve essentially the same problems. As thorny as these technical issues are, we should learn from the experience of the automobile industry and ensure these issues receive appropriate consideration in the development process.

4. Duration of inflation

Another important consideration in the design of the CABS must be duration of inflation. Many helicopter crashes involve multiple impacts. Typical multiple impact scenarios include crashing into trees, bouncing over uneven terrain, partial recovery from an initial impact, and wire strikes. It is essential that the air bags be available for the major impact, which may occur late in the impact sequence. This requires that duration of inflation be balanced with air bag firing thresholds as noted above. Another important consideration is that the bags will probably have to be vented to ensure that occupant interactions with the inflated air bag result in plastic deformation of the bag to minimize the rebound energy imparted to the occupant. As discussed for the out of position problem, this issue may also require consideration of advanced technology such as multiple inflators.

CONCLUSIONS

Contact injuries resulting from excessive flailing of the head, upper torso, and extremities remains the major source of serious and fatal injuries in crashes of Army helicopters. Inflatable supplemental restraint systems offer the best solution toward reducing contact injuries in helicopter crashes. The recognition of these facts led to the IBAHRS and CABS development programs. Both systems offer increased restraint during crashes with minimal restrictions imposed on the mobility and comfort of air crewmembers. The CABS consisting of multiple air bags per crewmember, distinctly offers the higher level of protection in a crash. However, a full CABS may not be technically feasible in certain cockpits due to the difficulty in finding appropriate "real estate" for mounting an air bag module, particularly in retrofit programs. Consequently, a hybrid system may be most appropriate for certain cockpits, using side air bags to protect laterally and IBAHRS for reducing forward flailing.

Through the judicious use of inflatable restraint systems combined with current crashworthiness technology, numerous studies have shown that there is the potential to reduce serious injuries in survivable crashes of military helicopters by 30 to 50 percent. There are a number of technological and fiscal challenges remaining until these systems can be fielded, but these challenges can be readily surmounted given appropriate emphasis by the developmental and operational communities. In achieving that result, it

is critical that technical leaders do not underrepresent or underestimate the time and cost involved in overcoming the remaining technical problems.

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Integration and Safety Issues Identified In Fielding of a Cockpit Air Bag System

Kent Wieter and Mike Curran
Aircrew Integrated Systems Project Manager's Office
Redstone Arsenal, AL

MISSION NEED

Improvements in crashworthy systems have greatly enhanced survivability in Army helicopters. Low elongation polyester is being used in aircraft seat restraint systems in lieu of the nylon webbing. Three axis sensing autolock MA-16 inertia reels are replacing older MA-6 and MA-8 strap acceleration locking reels. Helmets and other personnel protection devices are now more crash tolerant than ever before. Newer helicopter airframes utilize both stroking seats and energy absorbing landing gear. As a result, very few aviators are suffering "deceleration" injuries. Although significant advances in accident prevention, crashworthiness, and individual protective equipment have greatly reduced the potential for serious injury in a crash, pilots are still receiving fatal and major injuries in helicopter accidents. Cadaver testing indicates excessive head and upper torso motion due to body compression, restraint elongation, and compaction of webbing on the inertia reel and body deformation from high restraint loads. Combine this with the ever-increasing head borne mass items (Night Vision Goggles, Helmet Display Units, etc.), the aviators are still at risk of injury and death in a crash.

Even with the aforementioned improvements, it has been shown that five out of six injuries are due to aircrew members striking the aircraft structure. The most serious form of disabling or fatal injury identified in helicopter crashed was head injury. Head trauma was cited as the cause of death in more than half the fatalities incurred in survivable crashes. After review of U.S. Army Safety Center accident data, an U.S. Army Aeromedical Research Laboratory (USAARL) study indicated that an air bag system in all Army rotary wing cockpits has the potential to reduce fatalities in survivable crashes by approximately 23 percent, or roughly 3.3 lives per year. In addition, the study showed that major and minor injuries could be reduced by approximately fifty percent.

WHY CABS?

Crash survival devices are essential to save lives and prevent injuries. Other than the emotional stress of a lost life, there are cost factors involved in retraining new pilots, long term care for disabled aviators, and down time for care of injuries. Helicopters crash in a variety of ways, with extremely high crash pulses. There are also multiple strike hazards present within the cockpit, including; cyclic, collective, armor panels, instrument panels, glare shields, doors, gun sights. The safest way to protect the aviator is to remove

him/her from the cockpit prior to the crash. Ejection seats are not feasible due to weight, space, cost and helicopter dynamics, so another means of protecting the aviators is required. Based on automotive data, air bags have been shown to save lives. A cockpit air bag system would be the next natural transition from automotive technology to Army aviation. A forward and lateral air bag system can provide protection from major strike hazards in the cockpit. No other system afforded the level of protection from these type hazards as well as the CABS.

The results of an Army program, Development of a Helicopter Air Bag Crash Protection System, demonstrated that a CABS provides required protection in aircraft accidents. An AH-1 Cobra gunner crewstation mockup, including a Telescopic Sighting Unit, was used for 18 dynamic tests. The test severities were selected to be consistent with crashworthy aircraft structure and seat requirements (30G, 50-fps delta V). Automotive air bag generators and bag materials were selected for this program. The results of the dynamic tests indicated an 82% reduction in peak head G's. The air bag system converted fatal Head Injury Criteria (HIC=2500) head strikes to a non-injurious level (HIC=580).

BACKGROUND

In 1989, recognizing the potential for protection that may be afforded by an aircraft mounted air bag system, the U.S. Army Aviation Applied Technology Directorate (AATD) awarded a Phase I Small Business Innovative Research (SBIR) contract to investigate air bag technology for use in rotary wing aircraft. Based on the positive results of the Phase I effort, a Phase II SBIR contract was awarded in December 1991 for demonstration of an air bag system in an attack helicopter utilizing "off-the-shelf" automotive air bag technology. As a result of the Phase II effort, a Phase III SBIR contract was awarded in May 1994 to identify/develop air bag technology/components suitable for application in an aviation environment with new emphasis on aircraft with side-by-side seating arrangements. This Phase III effort, known as the Joint Development of a Cockpit Air Bag System (JCABS) program, was a U.S. Army led joint program with the Navy, Air Force, and Federal Aviation Administration (FAA) involvement using the UH-60A/L as the technology demonstrator. The JCABS technology demonstrator program served as the basis for all future CABS contracts. This program focused on development of requirements for air bag materials, gas generator performance and crash sensor performance. These requirements were then reviewed and tested for incorporation into a CABS performance specification.

Based on the technology maturity achieved under the JCABS and predecessor contracts, an Engineering and Manufacturing Development (EMD) contract was awarded in September 1996. During this phase, the air bag design was finalized, the gas generator requirements were refined and demonstrated, and the Electronic Crash Sensor Unit (ECSU) was finalized. The entire CABS was integrated into the airframe and the system tested for performance and reliability to strict military standards. Concurrent with the successful completion of the UH-60A/L CABS Critical Design Review (CDR) in June 1998, another contract was awarded in May 1998, under the auspices of the Kiowa

Warrior Safety Enhancement Program (SEP). The contract was for the Non-Recurring Engineering (NRE) required to adapt the UH-60A/L CABS technology and a commercially available automotive lateral protection device known as the Inflatable Tubular Structure (ITS) for use in the OH-58D airframe. Under this program, CABS components are modified for integration into an OH-58D. A common ECSU, similar sized air bags using common gas generators, consistency in bag materials and covers are used to qualify the system based on similarity and reduce the number of tests and ultimately reduce the integration and support costs. The final deliverable from the CABS EMD program will be a production ready performance specification. This document defines all performance/interchangeability requirements down to and including the replacement part level, to include all verification procedures required assuring compliance, which will be used to stimulate a competition on future CABS procurements.

CABS TEAM CONCEPT

The U.S. Army CABS program is being managed utilizing the Integrated Process and Product Development (IPPD) process. IPPD is a management technique that integrates all acquisition activities starting with requirement definition through production, fielding/deployment, and operational support in order to optimize the design, manufacturing, business, and supportability processes. Additionally, the IPPD approach is being emphasized in all CABS disciplines in order to integrate consideration of product design, related manufacturing, and logistics support requirements beginning with concept initiation and continuing throughout the product life cycle. The IPPD process is used to balance risk between cost, schedule and performance. At the core of IPPD implementation are Integrated Product Teams (IPTs). The IPT is composed of representatives from all appropriate functional disciplines (including both government and contractor representatives as appropriate) working together with a team leader to build a successful and balanced program/design, identify and resolve issues, and make sound and timely recommendations to facilitate decision making. Overarching IPTs will be used to obtain management guidance, program assessment, and issue resolution. Working level IPTs will identify and resolve program issues, focus on program status/execution, and seek opportunities for acquisition reform/streamlining.

INTEGRATION AND SAFETY

At first glance, taking an automotive inflatable restraint and it integrating it into a helicopter may not look too difficult. There are many differences to be considered, hurdles to clear and boxes to be checked before a new system can be installed into a military aircraft. The acquisition rules surrounding how this is to be done are constantly changing. The push is for acquisition reform; to do it faster, to do away with the tasks that have little or no value added. Acquisition reform calls for the use of performance specifications in lieu of detailed Technical Data Packages (TDP). The acquisition guidance is clear but the laws and attitudes have been slow to change. CABS is one of the first systems to be developed using acquisition reform and a performance spec and

has in many instances threatened organizations with being streamlined out of business. These attitudes could become a significant hurdle to program completion.

Personnel can have a major impact on a program. On a program such as CABS that has been around for six years there is a significant personnel turnover. Military participants change jobs every three years or more often than that. The Government civilian and contractor personnel have also experienced turnover during this period of time. In addition because of the Base Realignment and Closure Act, PEO Aviation and ATCOM moved from St. Louis, MO to Huntsville, AL. The move took over six months. Many employees chose not to move and all the files were unavailable for review much of the time. Every time a new person is introduced they come with their preconceived ideas and have to be brought up to speed with the program.

The airframe program management office can be a large hurdle to overcome. Consider the concept, that you are developing and designing a piece of equipment that is going to go onto an aircraft that is under the charge of a Program Manager (PM) or Product Manager that is responsible for all aspects of the airframes performance. Couple this with the PM being in another organization (PEO AVN vs. AMCOM) that has other priorities can be a challenge. All parties have the interest of the soldier in mind but the priorities don't always match. This points out the need to have programs like CABS in a separate program office to maintain the proper priority. This also emphasizes getting the affected parties involved early in the program using the IPT process. After all an inflatable restraint doesn't make the aircraft go faster, carry more weight or shoot better. This is an obstacle to overcome to have a successful program.

Marketing of the product is important in a program like CABS. There are positive and negative perceptions held by most people surrounding a system as controversial as CABS. A lot of these perceptions are given fuel from the media. The negative publicity comes from the fact there have been air bag related fatalities. The message heard by the general population is that air bags kill. The fact that it has been mostly small, elderly women and infants is irrelevant. Usually no mention is made in an article of this nature of how many lives are saved vs. those lost. When making the transition to military aircraft these negative images and perceptions carry over even though there are no elderly women or infants operating the aircraft. When dealing with aircraft and the first thought that jumps to the forefront is inadvertent deployment, "air bags kill". The media has covered instances of air bags inadvertently deploying in automobiles. What happens in an aircraft? Will the pilot lose control of the aircraft? What happens while wearing the equipment peculiar to aviators? Will the air bag poke my eyes out if I am wearing NVGs? These are examples of some of the scenarios that must be considered when working a program of this nature. The PM must have a effective marketing strategy combined with and intensive testing program to combat the negativity and resistance to change.

To have a successful program it must be adequately funded. A program such as CABS has to compete for funding at the ARMY level, the PEO level and within the PM office. A program manager must also be able to survive in a changing environment, where the

competition for funds is always a threat to programs. A recent example of this is the new Chief of Staff of The Army, General Shinseki just unveiled his vision of a lighter more deployable Army. General Shinseki is wasting no time in starting to implement his new plan and this will undoubtedly cause all programs to be examined, restructured or terminated to fund this new direction. The best strategy for competing for funding in today's environment of tight resources is to have a product that works as advertised, and have it quickly. The competition to obtain funding is made harder by the fact CABS is a controversial system.

Taking an off the shelf product used on automobiles and adapting it for use on military aircraft especially helicopters is a large and daunting task. Automobiles are pretty standard in their design, and usually crash in one axis. They are reliable but not built to meet the abuses of military life. Military aircraft on the other hand come in all shapes and sizes and in different configurations, such as side by side seating or tandem seating. Aircraft crash in multiple axis and are operated in extreme conditions. Adapting a system to multiple types of aircraft that are built to different specifications and operating environments only complicates the problem. In order to keep cost under control, a large number of the components must be standard between the aircraft being modified even though they are of different configurations. The system must then compete for space weight and power on the host aircraft. This is difficult because PMs are very concerned about the space and weight. It's been said, "they would hang a bathtub on this airplane if they could get away with it." Once space has been found and power allotted, an off the shelf system must be made to sustain and operate in the military environment. A system used in military applications must be able stand up to very extreme electromagnetic environments and harsh environmental conditions. Operating temperatures from –65°F to +160°F are not unusual. An aviation system must be able to withstand variations in pressure altitude, and continue to operate for extended time in a salt air environment. Military aircraft are also unique in that they are subjected to gunfire vibrations up to 30MM, and launch stresses of guided missiles and rockets from their pylons. Vibrations from the rotor system and various landing conditions are also present. The system must be reliable and able to withstand the above conditions and more. Reliability is important in that the system must not negatively affect the inherent reliability of the host aircraft.

TESTING

Once the design has been frozen at the Critical Design Review (CDR) all the conditions for operation and supportability have been identified. The system must be tested to insure that it can function as advertised in the military environment. Testing can be a long and expensive process. The restraint system should be tested to crash pulses to which the aircraft was designed (MIL-STD-58095 and /or to Federal Aviation Regulation (FAR) part 25). The developmental contractor will accomplish the developmental testing to reduce the risk that the system can meet the conditions the system will see in qualification testing. Most qualification testing is performed by a combination of contractor conducted tests and Government conducted test. This decision of who will conduct the testing is usually decided on issues of cost, schedule and asset availability.

Testing for an inflatable restraint system can run from one million to two million dollars. The testing will usually fall into three categories; performance, environmental and reliability. For performance testing dynamic crash testing is an accepted method. There are several facilities to accomplish dynamic testing testing. The Navy, Air Force, FAA all have Government dynamic testing facilities and some contractors also have facilities for conducting dynamic crash testing. To accomplish the dynamic testing cockpit mockups have to be constructed. Considerable care has to be taken to make sure the mockup is representative to the actual aircraft. If this is not done test results will be invalid. All test results must be compared to some criteria to measure the performance of the system. For CABS the only data available is from the automotive industry. They have completed considerable research, to develop limited injury criteria. The data gathered from dynamic testing is used to evaluate the restraint systems performance in a crash scenario. A panel of experts made up of Government and non-Government personnel does the evaluation of the CABS data.

The environments that military systems must operate in and be exposed to are very severe. The most severe are the extreme temperature ranges and the corrosive environments found aboard naval vessels. Both the component subsystems and system level require testing to ensure that the environmental requirements are met. Below is a listing of the environmental tests an inflatable restraint would be required to perform in.

a. Combined Temperature/Pressure Altitude - (MIL-STD-810, Method 520, Procedure III). The temperature, pressure, and humidity varied during in a four-hour cycle. The temperature varied between –25 and 130°F and the altitude between 0 to 20,000 feet. The relative humidity remained at 75 percent at 55°F but uncontrolled at other temperatures. Test articles were subjected to 10 such cycles.

b. Solar Radiation - (MIL-STD-810, Method 505.3, Procedure II). Solar radiation requirements were evaluated by similarity of the CABS materials and finishing processes. (No solar radiation testing was performed.)

c. Humidity - (MIL-STD-810, Method 507.3 Procedure III). The temperature was varied between 85°F and 130°F over a 24 hour cycle with relative humidity maintained between 85 and 95 percent. Test articles were subjected to 10 such cycles.

d. Fungus - (MIL-STD-810, Method 508.4). Test articles were conditioned for a minimum of 4 hours at 75 to 88°F and 95% relative humidity and then inoculated with a mixed fungal spore suspension. Incubation was performed on a daily cycle consisting of 20 hours at 86$\pm$2°F and 95% relative humidity, followed by a 4-hour transition to 77°F maintained for at least 2 hours. A minimum 24 cycles was completed. There was no fungal growth on the test articles in conjunction with fungal growth on the control samples.

e. Salt Fog with Stack Gas - (MIL-STD-810, Method 509.3). Two cycles was conducted with each cycle consisting of a 24-hour exposure to salt fog followed by a 24

hour drying time. The chamber was maintained at a temperature of 95°F and ambient pressure altitude. The salt concentration was at 5% and stack gas was injected once during each six hour (4 times) of test during the 24-hour salt dog exposure period.

f. Sand and Dust - (MIL-STD-810, Method 510.3, Procedures I & II). The sand was maintained at a concentration of $2.2 \pm 0.5 m/m^3$ and a velocity of 18 meters/sec for six hours at 130°F. Relative humidity was maintained at 30% or less throughout the test. The ECSU was operating during the last hour. The test articles were reoriented at 90-minute intervals throughout the test. The dust was maintained at a concentration of $10.6 \pm 0.7 m/m^3$ and a velocity of 8.9 meters/sec for six hours at 73°F. The temperature was then increased to 130°F for another six hours at the same velocity and concentration. Relative humidity was maintained at 30% or less throughout the test. The ECSU was operating during the last hour. The test articles were reoriented at 90-minute intervals throughout the test.

g. Shock - (MIL-STD-810, Method 516.4, Procedure I).

1. Functional Shock: A shock meeting the requirement levels and duration of MIL-STD 810E, was applied three times in both directions along each of the three orthogonal axes, for a total of 18 shocks.

2. Transit Shock: Transit shock was evaluated by analysis. The analysis considered shocks delivered during dynamic testing as being more severe than any shock expected by CABS packaged for transit.

3. Crash Hazard Shock: Crash hazard shock was evaluated by analysis. The analysis considered that the dynamic tests exposed the CABS in a field representative installation to levels higher than those required by MIL-STD-810E crash hazard shock tests.

h. Vibration - (MIL-STD-810, Method 514.4, Category 6): All components will be tested for a duration of four hours of excitation for each of the three mutually perpendicular axes for a total test time of twelve hours per component. These vibration levels were collected from instrumentation installed at the same location as the CABS components during actual UH-60 normal flight maneuvers, hard landings, and weapons engagements. (This data must be collected for each aircraft.) To support reliability tests, the ECSU shall be exposed to 1974 hours of vibration at levels representative of the aircraft. The 1974 hours will be divided to support each of the three axes and transitional activities at ambient and extreme temperatures.

Another environment that is especially important is the electromagnetic environment (E^3) in which the system must function. This is especially true when operating in a naval environment in close proximity of large powerful shipboard radar. This testing is performed in accordance with ADS –37A PRF. Electromagnetic Interference (EMI) must be tested on a system at the bench level. Electromagnetic Vulnerability (EMV) and Electromagnetic Compatibility (EMC) must be conducted on the aircraft at a special

facility operated by the Navy. Hazards of Electromagnetic Radiation to Ordinance (HERO) testing is also conducted at the aircraft level at a facility operated by the Navy. EMI, EMV, EMC and HERO are all necessary to obtain an Airworthiness Release. Systems with electronic components such as the Electronic Crash Sensor Unit (ECSU) also have to be able to tolerate near strike lightning and static electricity from handling.

Most inflatable restraints will use some type of cartridge activated inflator, whether it be a compressed gas cylinder or gas generator type. Gas generator inflators or any other type of cartridge activated device will require Service Release Testing (SRT) for use in the military services. This testing is very extreme and exposes the device/component to high temperatures, direct electrical currents, fire, vibration and drop tests. These are examples of some of the testing performed. This is done to characterize the behavior of the devices before they enter military service. The Navy provides this testing service for all the Services. This testing is expensive because of the amount of hardware consumed and the nature of the specialized testing.

The specification requirement for probability of inadvertent deployment is 10^{-9}. This requirement cannot be demonstrated due to cost and schedule constraints. Additionally, inadvertent deployment is such a sensitive subject that additional testing is required. Injury potential of deploying air bags needs to be evaluated using Anthropometric Test Dummies. Simulation of the air bag effects on flight controls has to be reviewed to see if there is any detriment to control. This data is then evaluated to determine if it is safe to deploy air bags on the pilots in flight. When approval is granted, the air bags are deployed in the aircraft during normal flight maneuvers. Not all flight scenarios and occupant positions can be defined, and certainly not tested. A balance of simulation and actual flight must be established to insure safety of the pilot during deployment.

The final test series that must be conducted is reliability testing. This is necessary to provide some indication that of the systems inherent reliability. This is always a shortcoming in a system's test program because of the large number of hours needed to prove out reliability. It is cost prohibitive to have enough flight hours to prove out reliability. The most cost effective and quickest method is use a combination of aircraft flight hours and shaker table testing. Even using this method will not get enough test time to completely prove reliability. This testing usually takes the longest time to complete. A system such as CABS will take 1,974 hours to prove reliability out to .999.

Testing is a costly and time-consuming process. A lot of questions are answered and issues do arise which need to be resolved. Enough testing must be performed to insure performance and safety. Care must taken to insure that the program does not fall into a testing "black hole". Test requirements must be established up front and approval of test plans from the evaluators must be obtained prior to start of testing. This reduces the possibility of having to perform additional testing at a later time.

APPROVAL FOR FIELDING

The last process to be completed for the integration of a system into an aircraft is to get the Engineering Change Proposal (ECP) and Modification Work Order (MWO) completed. The airframe prime contractor usually performs this effort with support from the restraint system prime contractor. Ideally these two contractors would be working with each other from day one. This process can be time consuming and expensive depending on the complexity of the integration. The ECP documents the changes made to the aircraft. The ECP also updates all the operators and maintenance manuals, training and drawing packages. The MWO is the installation instructions and any other special instruction necessary to install the new system into the aircraft.

The airworthiness release is the official document that allows the aircraft to be flown with the new system installed. An analysis of all the testing data is reviewed by AMCOM engineering and after that review, an airworthiness certificate is issued. This can also be a time consuming effort. Most agencies whether it be the FAA, Army, Navy or Air Force practices a conservative approach to issuing an airworthiness certificate.

CONCLUSION

Air bag systems, proven to be effective in automobiles, have been determined to be equally valuable in rotary wing aircraft. Many integration, testing and safety issues need to be addressed prior to fielding of such a system. The key to a successful program is early involvement of the affected members of the integration team. With participation by the host aircraft manufacturer, project managers, all of the support members and the development contractor early in the program, there are less issues and surprises down the road. Issues with funding and preconceived notions need to be addressed through out the entire program. And lastly, keeping every one current and part of the decision process will help alleviate most of these problems.

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Airbag Performance and Design Issues for Naval Aircraft Applications

Michael R. Schultz
Ann C. Schoenbeck
Naval Air Systems Command
Crashworthy Escape Facilities Branch
Patuxent River, Maryland, USA

Gil Wittlin
Dynamic Response, Inc.
Shermen Oakes, California, USA

ABSTRACT

Crash protection systems have in the past been designed using criteria and design approaches based solely on ground impact conditions, without considering fundamental differences associated with water crashes. The U.S. Navy is addressing this shortcoming by conducting research in the area of water impact crashworthiness, and is applying this research to airbag applications through involvement in the joint service Cockpit Airbag System (CABS) program led by the U.S. Army. Two specific areas of research applicable to the CABS include the study of water impact crash dynamics, and underwater egress from an inverted helicopter. A summary of this research is presented, including results of full scale helicopter crash tests into water, structural crash modeling of water impacts, and underwater egress tests using airbags in the Navy's Mk-9D5 underwater egress training device. Implications of this research are discussed regarding calibration of crash sensors and overall design/performance issues for airbags.

WATER CRASH DYNAMICS & INJURY TOLERANCE

Aircraft crash onto many types of fundamentally different surfaces, each of which place differing demands on airframe crashworthiness designs, and the design of crash protection subsystems such as airbags. Typical impact surfaces include rigid surfaces such as runways, soil with its range of compressibility properties, rocky terrain, and water of varying depths and sea states. In actual crashes some of these surfaces can be combined, highly uneven, and include obstructions such as trees. Although military and civil aircraft experience crashes on each type of surface, current crashworthiness criteria are based mainly on flat rigid surface impact characteristics. For example, crash pulses used for design criteria and compliance testing of load attenuating seats (MIL-S-58095) are based on a rigid surface impact assumption. Likewise, similar crash pulses are being applied for development of aircraft airbag systems. This practice

has been accepted in the past because most of the available data on aircraft impact characteristics were associated with rigid surface impacts, and it was assumed that aircraft designed for rigid surface crashworthiness would have acceptable performance when impacting other surfaces.

The U.S. Navy is currently sponsoring research to expand crashworthiness knowledge into the area of aircraft water impacts. The research also has applicability to crashes on soft soil due to similarities. The FAA is cosponsoring this research being performed through a Small Business Innovation Research (SBIR) contract to Dynamic Response Inc. Bell Helicopter Textron Inc. and Simula Technologies Inc. are participating as subcontractors. Objectives of the SBIR are to establish a crash simulation capability for water impacts, investigate combined crashworthiness criteria for both land crashes and water crashes/ditchings, and to propose design enhancements for follow-on consideration and development. The research includes full scale crash testing into water.

Water Impact Pulses

While the Navy's water impact research is still in-process, several findings have emerged that could be used to improve airbag performance and test criteria to cover water impacts as well as ground impacts. One of the findings is that acceleration pulses associated with helicopter crashes into water have significantly higher onset rates (and shorter rise times) than that of ground impacts. Figure 1 shows impact acceleration pulses taken from crash simulations of Navy SH-60 helicopters

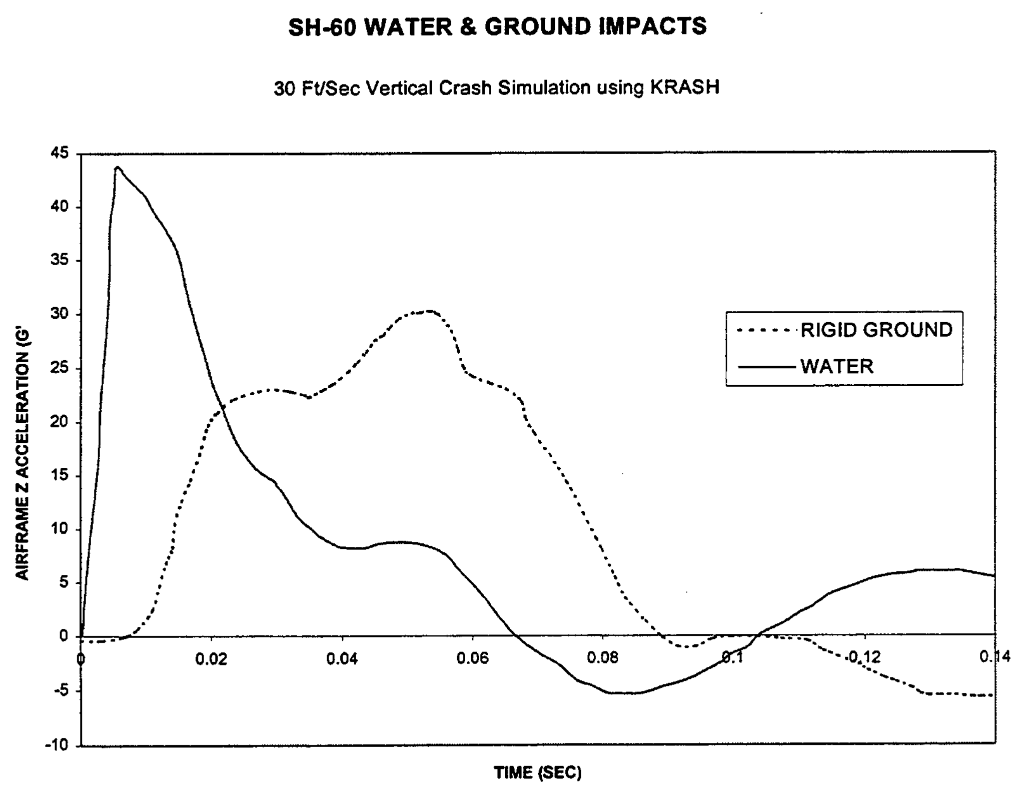

Figure 1: Ground and Water Impact Simulation Results for the SH-60

undergoing vertical ground and water impacts at 30 ft/sec. The simulations were performed for the Navy by Dynamic Response Inc. using the KRASH modeling and simulation code. Simulation results predict that the acceleration onset rate of the airframe would be approximately 580 g/sec for the ground impact and 8,800 g/sec for the water impact. The rise times for the crash pulses are approximately 52 ms for the ground pulse and 5 ms for the water pulse. In this these simulations the SH-60 landing gear had a negligible effect in both the water and ground impacts.

Figure 2 provides another comparison using data from full-scale helicopter crash tests onto rigid and water surfaces. In this case, the data are from crash tests UH-1H aircraft at different impact velocity and attitude conditions, and they serve to show how widely crash pulse characteristics can vary with combinations of different impact conditions. An acceleration onset rate of approximately 420 g/sec occurred with the UH-1H crash tested on a rigid surface at the NASA Langley Research Center at an impact velocity of 40 ft/sec vertically and 32 ft/sec horizontally. The aircraft impacted with a roll angle of 26 degrees, a nose up attitude of 10 degrees, and it was equipped with an external auxiliary fuel tank on the low side. A higher onset rate of approximately 5400 g/sec occurred with the UH-1H crash tested into water at the Army Yuma Proving Ground under the Navy's SBIR (Figure 3). This aircraft impacted in a flat attitude with an impact velocity of 26 ft/sec. When viewed from the standpoint of rise times, the rise time was approximately 10 ms for the water pulse and 90 ms for the rigid ground pulse.

Large differences between water and

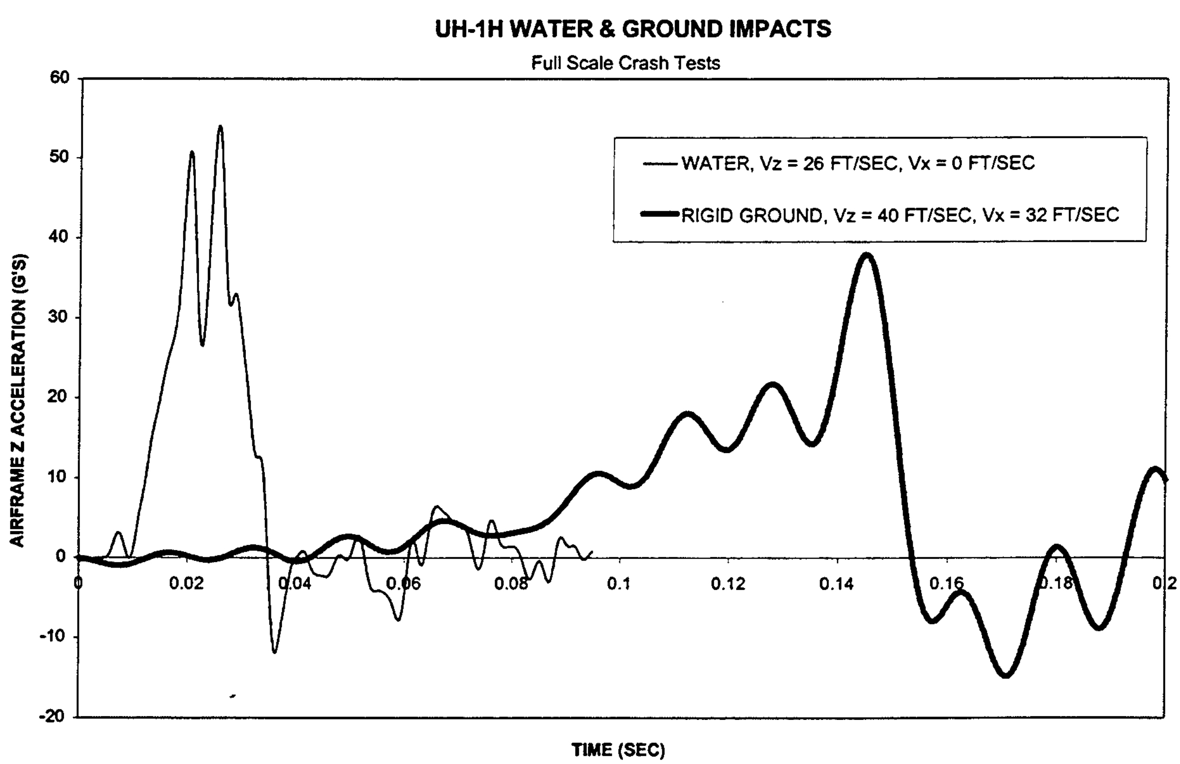

Figure 2: UH-1H Water and Ground Impact Results

rigid surface crash pulses are caused by fundamental differences in how airframes structurally respond to impacts on the two surfaces. Furthermore, the differences are even greater for aircraft that include energy absorbing landing gear, such as the UH-60, AH-64, and V-22. Regarding airbag applications, the variations in crash pulse signatures should be determined and taken into account when designing and calibrating a system for a particular aircraft. This is necessary to ensure that crash sensor response time and airbag deployment dynamics are properly tuned for occupant biodynamic responses to crashes on all anticipated surfaces. Under the Navy's SBIR, an additional water crash test was recently completed using a combined vertical and horizontal impact condition. That data will also be reviewed to assess crash pulse characteristics.

Crash Sensor Location

One location being considered for mounting an airbag crash sensor in the Navy's H-60 aircraft is the seat-well directly below the copilot seat. The sensor could be mounted in the well (intended for seat stroke) on the side of a longitudinal beam near the lower skin panels of the airframe.

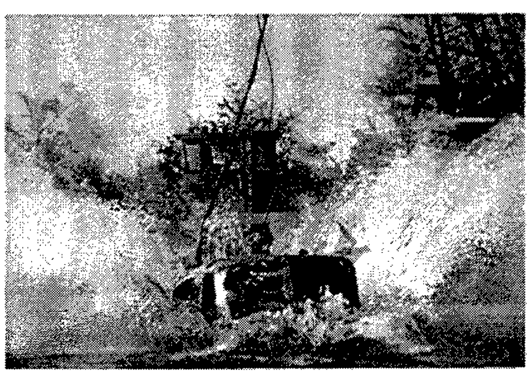

Figure 3: UH-1H Vertical Water Impact Test

This location initially seemed desirable due to its close proximity to the airbag modules, as well as the fact that the longitudinal beam is primary structure that can reliably transfer crash accelerations to the sensor. However, the full scale water crash tests of UH-1H aircraft revealed a potential vulnerability of that location.

In the water impact tests, the skin panels failed in various locations, including in the area directly beneath the pilot seats. If in an actual crash the skin panels began failing before crash sensor activation, the failed panel and/or hydrodynamic ram force of in-rushing water could damage the sensor or its connecting cables, preventing the airbags from activating. Detailed crash modeling and simulation are necessary to analyze the event sequencing and evaluate this potential problem.

Occupant Injury Tolerance

Testing of airbag systems has clearly shown that airbags can reduce head accelerations to survivable levels in many crashes. However, for crashes into water, injuries must not only be non-lethal, but they must also prevent unconscienceness or mental impairment. Due to the high center of gravity associated with overhead location of the engine, transmission, and rotor, helicopters usually invert and begin sinking immediately after impact. If an occupant is rendered unconscience due to high head accelerations while interacting with the airbag, drowning will likely occur. Even temporary mental impairment caused by head/airbag interaction could result in drowning because of the physical and cognitive demands of underwater escape

from a rapidly sinking helicopter. The same concern exists for ground impacts that include post-crash fire. Currently, the Head Injury Criteria (HIC) are used in airbag applications to assess acceleration based head injury. However, the HIC has not been validated as a means of assessing loss of conscienceness. Additional research is needed to provide acceleration-time thresholds for loss of conscienceness as well as other forms of injury.

UNDERWATER EMERGENCY ESCAPE

Whenever an inflatable restraint is designed for an aircraft whose mission involves extensive flying over water, the effect of the restraint design on the capability for aircrew to escape the airframe underwater and inverted must be considered. Inflated restraints will have positive buoyancy that will cause them to float towards the floor of an inverted aircraft and thus may hinder egress by "trapping" legs, feet, or shoulders as the aircrew attempt to escape.

The Navy has conducted underwater egress tests on the two inflatable restraint system programs. For the shoulder-harness mounted Inflatable Body and Head Restraint System (IBAHRS), testing was conducted in a pool using a 9H21 Shallow Water Egress Training (SWET) device. For the Joint Cockpit Airbag System program (JCABS), underwater egress testing was conducted using a modified 9D5 Dunker.

IBAHRS Testing [2]

In 1993, underwater egress testing was conducted on the IBAHRS system using the SWET device. This device was developed for Helicopter Emergency Egress Device (HEED) training. The HEED is a small bottle of compressed air for use in underwater emergency egress situations. The HEED, worn on the survival vest of aircrew, contains enough air for 2-3 minutes of breathing.

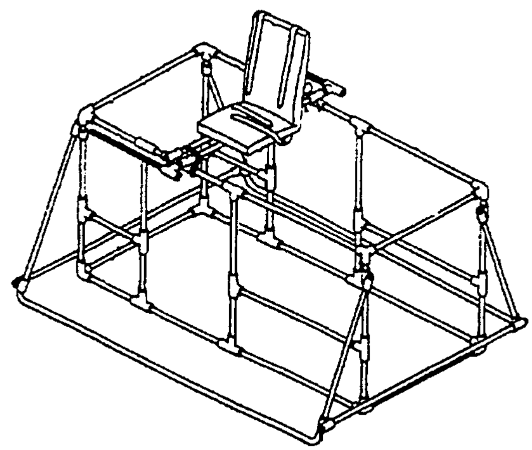

Figure 4: SWET Device

The SWET device (Figure 4) consists of a seat mounted on top of a metal framework. When it is placed in four feet of water, the seat pan is just above water level. After the occupant buckles the restraint system, the seat swivels so as to put the occupant upside-down and underwater. Then the occupant must remove the restraint system and swim out of the SWET cage.

Figure 5: Deployed IBAHRS Shoulder Harness and HEED

The IBAHRS testing was the first testing of an inflatable restraint system's impact on emergency egress that was conducted by the Navy. The biggest difficulty discovered during the testing was an incompatibility with the HEED bottle (Figure 5). Since the testing, the HEED has been redesigned and replaced by the Helicopter Aircrew Breathing Device (HABD) in the fleet (Figure 6). It is unknown what the impact of the combination of the HABD and an IBAHRS would be on emergency underwater escape.

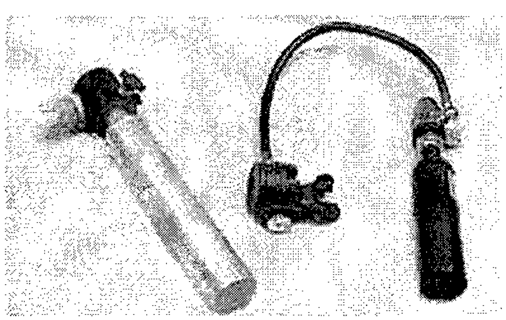

Figure 6: HEED Bottle and HABD

Another observation during the IBAHRS SWET device testing was that the inflated IBAHRS seek the water surface, so the occupant had to physically move the IBAHRS shoulder harness away from his body prior to escape. This is different from the standard restraint because the attachment hardware weighs down the shoulder harness and causes it to sink. In an inverted underwater situation, buoyant shoulder harnesses tend to push as occupant into the seat, but sinking shoulder harnesses remove themselves from the occupant's chest.

JCABS Testing [3]

In 1995, underwater egress testing was conducted with a mock-up of cockpit airbags under the JCABS program. The purpose of this testing was to simulate an underwater, post-crash environment in the SH-60 cockpit with the CABS deployed to determine the impact of the partially-inflated airbags on survivor egress.

Since the CABS airbags are not vented like automotive airbags, some level of residual gas will remain in the bag after deployment (an estimated 30-70%). This residual gas will cause the airbags to seek the water surface with varying degrees of force (proportional to the amount of gas remaining in the airbag). In the case of an inverted aircraft, this direction would be toward the cockpit floor. The airbags that float towards the cockpit floor can potentially trap a crewmember's legs. Cockpit airbags may also impede egress by blocking an escape hatch or becoming an obstacle in an escape route.

A modified 9D5A dunker was used to test the system. The dunker simulates a

helicopter during a water impact scenario. It consists of a cylindrical shell that is lowered into the water and can be inverted (this represents a typical reaction of a helicopter after water impact). The test subjects were restrained in the dunker during water entry and inversion. The test subject's ability to egress the inverted device was then evaluated. The 9D5A dunker cockpit was modified to represent the H-60 cockpit by adding a center console, installing simulated emergency exit handles, modifying the instrument panel and glare shield, moving the seats to a more SH-60 representative location and reducing the side window exits to representative size and shape of the SH-60 windows (Figures 7 and 8). The copilot seat was lowered approximately 12 inches to represent a stroked SH-60 copilot seat. Four airbags were installed in the cockpit in their planned mounting locations, one in front of each pilot attached to the under side of the glare shield and one on each side attached to the aft bulkhead. The airbags were inflated to various levels to represent different airbag volumes and potential blockage scenarios (the CABS airbags are not vented to the atmosphere and reduce in volume due to decreasing gas temperature after inflation).

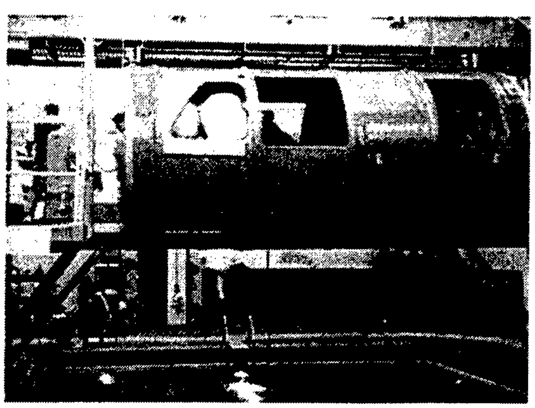

Figure 7: Airbags Installed in 9D5 Dunker

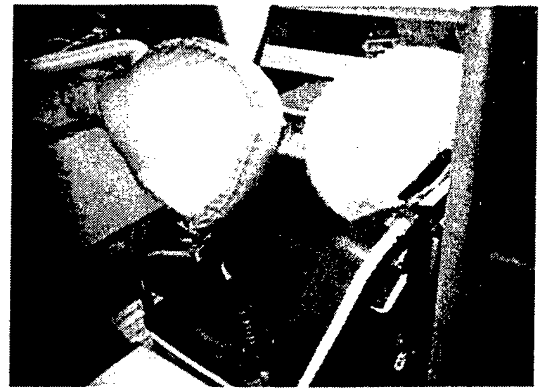

Figure 8: Airbags Installed in 9D5 Dunker Cockpit

The testing occurred in three phases. Phase I was a safety check that took place in Pensacola, Florida. Airbags were installed in the cockpit of a 9D5 dunker and inflated. Checks were made to determine occupant safety, clearances, and ability to reach emergency exit handles

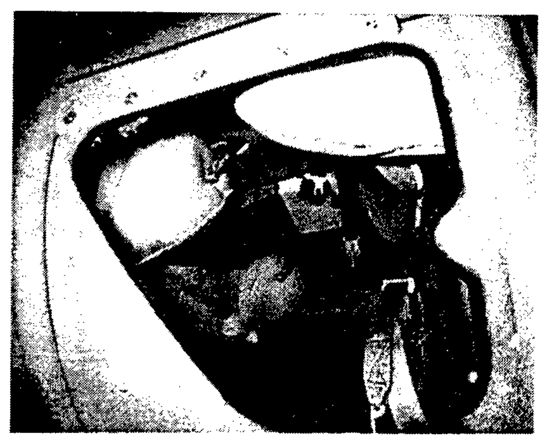

Figure 9: Airbag Buoyancy in an Inverted Dunker

The second and third phases of the test program were held at Miramar, California. The airbags were installed in the 9D5 dunker. In Phase II, Navy divers/qualified NAWSTP instructors performed underwater egress with 9D5A in upright and inverted positions. Qualified Navy divers also evaluated the

use of the HEED while exiting the cockpit with inflated airbags.

In Phase III, volunteer helo aircrew performed underwater egress with CABS installed using procedures developed in Phase II. Testing with the aircrew included evaluating a stroked vs. unstroked seat, cross-cockpit egress, and egress with blacked-out goggles. Airbags were studied fully-inflated and partially-inflated.

Test subject comments included the following:

1. The forward bag snagged/blocked some test subjects' legs and feet between the front edge of the unstroked seat and airbag in the 180° dunker position. This blockage required them to turn their foot 90° to free it for egress (Figures 9 and 10).

Figure 10: Airbags in Underwater Dunker Test

2. The side airbag pushed on some test subjects' head/shoulders during aircraft roll and when inverted. This condition happened only in the seat that was on the side of aircraft roll as it entered the water. The opposite dunker side was free, and because there were no egress hatches/windows installed, the airbags floated freely outside the dunker. If there had been egress hatches/windows installed, the airbags would have reacted against them causing unknown results. Some test participants commented that follow-on testing should be done with simulated emergency escape hatches to understand how these hatches react with the side bags.

3. Some test subjects had the airbag(s) obstructing their access to the simulated emergency exit handles during roll and when inverted. This required the test participants to move the airbag to reach and activate the egress hatches/window release handles.

4. All subjects commented the airbags did not significantly deter their emergency egress during these tests.

5. All subjects commented, "If the airbags are in the aircraft, then they should be included in the 9D5A training."

6. Some test subjects mentioned the use of the dry suit during this test could be more challenging.

Due to the limitations of the testing and the idealized conditions under which testing occurs, the effect of CABS on egress in an actual crash situation cannot be fully evaluated. However, comments received from this testing can point to potential egress problems caused by the incorporation of airbags into a SH-60 cockpit.

There were 24 tests run - most with two occupants. In the 45 egresses, there were 20 mentions of the front airbag pushing on or trapping the feet or legs of the test subject. Seventeen of these occurred in the unstroked seat and the remaining three occurred in the stroked seat. In all of these cases, the test subject was able to free himself.

Eight mentions were made of the side airbag pressing on the side of the test subject during rotation (four on the stroked seat and four on the unstroked seat). Six mentions were made of the airbag rotating behind the head or back (four for the stroked seat and two for the unstroked seat).
Five mentions were made of the side airbag causing difficulty in locating the release handle of the window exit (one for a stroked seat and four for the unstroked seat). One subject in a stroked seat mentioned that the airbag pressed on his side, rotated behind his back and pushed him forward. Since he was in an awkward position, he had difficulty locating the release handle.

CONCLUSIONS

Significant differences exist between ground and water crashes of helicopters, and it's important to take these variations into account when developing aircraft airbag systems. Similar differences also exist for crashes into soft soil. Higher acceleration onset rates associated with water impacts should be evaluated in terms of crash sensor calibration and the dynamics of airbag deployment verses occupant motion. Choice of the crash sensor location should take into account the possibility of skin panel failures that could disable the crash sensor before firing if the sensor is mounted on subfloor structures. To avoid drowning, airbags should be designed to not only avoid lethal head injuries, but also non-lethal injuries that could cause loss of consciousness or temporary mental impairment. Lastly, the airbags and their locations should be assessed to insure they do not restrict safe underwater escape from inverted helicopters.

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Air Bag Related Eye Injuries: The Automotive Experience

Alfred P. Bowles, II, MD
Biodynamic Research Corporation
San Antonio, Texas

ABSTRACT

Passive occupant restraint was mandated by the federal government in an effort to reduce road traffic crash-related casualties. The automobile manufacturers have designed supplemental inflatable restraint systems into production vehicles in order to respond to this need. Although a significant statistical reduction in fatality and life threatening injury has been demonstrated by the introduction of air bag restraints in the vehicle fleet, the potential exists for injury related to air bag deployment. The energy required to effectively deploy an air bag into the occupant compartment of the motor vehicle in a carefully-timed, split-second interval has the potential for inflicting injury to the structures of the human eye. Rapidly deploying components of the supplemental restraint system, interposed objects and occupant proximity to the inflator module are factors that predispose an occupant to deployment-related eye injury.

INTRODUCTION

Air bags are a component of supplemental inflatable restraint systems that are designed to work in concert with other components of automotive passenger protection and safety systems to reduce the incidence of serious injury and fatality associated with road traffic crashes. Over the past two decades, increasing numbers of air bags have been placed into service. As real-world collisions occur, vehicle crash researchers have gained increasing experience with the outcomes of crash-related air bag deployments. The complexity and sophistication of supplemental inflatable restraint systems has also evolved with the lessons learned from field performance and product development testing. Unlike the safety devices traditionally utilized in the automotive environment, inflatable restraints add energy into the collision event, and occasionally, the addition of energy is placed in close proximity to the occupant. The energy associated with an air bag deployment must be of a sufficient magnitude to offer additional restraint to an unrestrained occupant in the collision events likely to be encountered in the highway environment. Assuming that an air bag deployment is desirable in a frontal crash in which a life-threatening injury may occur, the requirement for supplemental restraint energy encompasses a more than ten-fold range, if the system is intended to provide occupant protection for any event between the low end of collision severity to the upper range of a potentially survivable high speed collision. The ultimate performance of automotive inflatable restraints is affected by the multiple and complex pre-crash and crash-related conditions which must be managed by

a pre-determined output response. Crash events vary in severity and deceleration characteristics depending upon the contacting surfaces, angle of impact, and pre-crash vehicle dynamics. Occupants vary in size, age, driving habits and willingness to comply with belt restraint usage laws. Given the nearly infinite combination of possible crash events, the deployment of inflatable restraints has resulted in unintended consequences in certain cases, including the creation of injuries that would not have occurred from the incident crash had the inflatable restraint not deployed. The difficulty in engineering inflatable restraints for consumer-oriented passenger vehicles has centered around the minimization of unintended consequences and the optimization of crash injury reduction, and the desire to achieve perfection in this balance despite the wide variation in the ways consumers use the product.

HISTORY OF AUTOMOTIVE INFLATABLE RESTRAINTS

Passive and supplemental inflatable restraint evolved over the course of vehicle development in the twentieth century. The first conceptual patent for an automotive inflatable restraint was issued to Hetrick in 1953.[1] Earlier patents were issued for inflatable air cushion use in aircrew protection. By the 1970's, automobile manufacturers were building prototype systems and introducing test fleets onto the highway. The first governmental regulation to institute automatic protection of occupants was instituted in 1970, but was rejected the following year after a controversial court battle. In 1984 the FMVSS 208 passive restraint amendment brought about the phase-in of air bags or automatic seat belts between 1987 and 1990. In 1991, an extension of the amendment was passed to require automatic protection to occupants in light trucks. The Intermodal Surface Transportation Efficiency Act in 1991 required that all passenger cars, light trucks and vans provide air bag restraint for both drivers and front passengers.

According to the Insurance Institute for Highway Safety, in 1999, there were approximately 95 million vehicles on the road in the United States with driver air bags. Nearly 68 million vehicles also had passenger air bags. As approximately one million new cars entered the fleet each month, a greater portion of the passenger vehicles in service became equipped with inflatable restraints. It was estimated that there have been 3.3 million crashes in which air bags deployed as a result of crash-related dynamics, and in over 600,000 crashes, the right front seat was occupied by a passenger who experienced a passenger bag deployment. The performance of air bags has been reflected in the reduction of serious injury and mortality from traffic accidents. As of 1999, the Insurance Institute for Highway Safety estimated that 4,750 lives had been saved by the presence of air bag restraint, and that there had been a 26% reduction of belt-restrained driver fatality from air bags. A more substantial 32% reduction in fatality for unrestrained drivers has been reported.[2] Trends in injury patterns would also suggest that air bags have contributed to a reduction in significant life-threatening injuries.

A trade-off for injury and mortality reduction in high-energy crashes has been the unfortunate and unintended injury that has occurred with air bag deployment. The National Highway Transportation Safety Administration has investigated a number of

crash events and as of November 1999, concluded that 146 deaths were attributed to the inflation of air bags in low-severity crashes. These deaths include 56 adult drivers and 6 adult passengers, the majority of whom were unrestrained. Also included in the investigation are 66 cases in which children between the ages of 1 and 11 years received fatal injuries in low-severity crashes. In 53 cases, the children were unrestrained. Eighteen infants have died in low-severity crashes from apparent air bag related injury. These include 15 in rear facing infant seats and 3 infants carried on adult passenger's laps.[3] A review of fatalities attributed to air bag deployment indicates that out-of-position or unrestrained occupants are at highest risk for unintended deployment-related injury, and underscores the importance of belt restraint usage. Inflatable restraints are supplemental to the belt restraints, even though air bag systems are designed to reduce the severity of injury to unrestrained adult occupants in severe frontal impacts.

In order to provide adequate occupant restraint over a wide range of possible collision scenarios, a crash sensing strategy must trigger an air bag system to inflate by predicting the severity of a crash early in the event. Frequently, the prediction of crash severity must be made before the crash sequence has fully developed. In some situations, deployment may occur in a collision that is near the desired deployment threshold. It is the lower crash severity events in which crash-associated injuries are the least likely that unintended outcomes are most recognized. The challenge to the air bag design team has been to effectively discriminate the near-threshold crash from the more severe impact in time to effectively provide supplemental occupant protection. The accuracy of crash severity prediction remains a challenge, and may be improved with advances in crash detection. As technological improvements allow sensing systems to discriminate the various possible types of collisions and predict the nature of impact before contact occurs, multi-variable deployment decision-making algorithms could become capable of tailoring inflatable restraint deployments to maximize occupant safety in a diverse array of predictable crash scenarios.

The term "out-of-position occupant" is used to describe an occupant who has significantly moved out of the expected seating position and near or on the module prior to deployment of the air bag. An occupant may be out-of-position as the result of voluntary movement or positioning, pre-crash vehicle dynamics, or the seating position utilized to operate the vehicle. An occupant who is both out-of-position and in close proximity to the deploying air bag would be at increased risk for deployment related injury, since the energy density of deployment is highest near the inflator. The deploying air bag may also impart kinetic energy of significant magnitude to objects interposed between the inflator and the occupant. Items such as eyeglasses frames and tobacco pipes have been known to cause missile injury to occupants.[4,5]

OCULAR INJURY

The human eye is a delicate structure with a complex anatomy, and is vulnerable to both blunt impact and missile injury. The eye has a low tolerance to impact when compared to many other body structures. The skeletal frame and somatic muscle are capable of

managing many times the energy that would cause significant impairment of the ocular structures. Racket sports, fist-fighting and air rifle pellets are among the well-known mechanisms of sight impairment.[6,7] An analysis of the energy associated with deploying air bag fabric shows that the surface has similar energy densities as found in moving rackets, swinging fists and projectile toys, and that the folds and seams of deploying bag fabric are likely to possess kinetic energy in excess of the injury threshold for the eye. Peri-orbital injuries from air bag deployment include abrasions, lacerations and contusions of the eyelid and surrounding soft tissues. Surface injuries to the cornea and sclera resulting from contact with air cushion fabric or particulate liberated during the deployment of the air bag include abrasion, keratitis and conjunctivitis. These injuries are typically self-limited and of minimal long-term significance.

Anterior chamber injuries from air bag deployment include hyphema, angle recession, cyclodialysis cleft, and trabecular mesh tearing. Injury of the iris sphincter mechanism may disrupt the optical mechanics of the eye. The structures of the anterior chamber are also important in the regulation and maintenance of intraocular pressure. Disruption of the anterior chamber anatomy can lead to post-traumatic glaucoma. Posterior segment injuries from blunt impact include lens subluxation, lens capsule rupture, vitreous hemorrhage, retinal hemorrhage, retinal dialysis, choroidal rupture and retinal edema. Mechanisms of injury to the posterior chamber have been postulated as the result of animal studies which reflect a differential structural composition of the layers and the dynamic motion related to ocular wall deformation resulting from anterior globe impact.[8] Late findings after ocular injury from air bag contact are similar to the late clinical findings after other forms of blunt eye injury, and include the development of post-traumatic cataracts, glaucoma and retinal detachment.

Eye injury is not a unique outcome related to air bag deployment. Motor vehicle crashes have been a significant cause of injury to the eye for many years. As many as 15,000 eye injuries result from vehicle crashes each year, and it has been estimated that about 10% of ocular trauma results from crash injury.[9,10] The number and severity of eye injuries from vehicle crashes has been decreasing over the past decades, due in part to improvements in medical procedures to maintain and improve visual function after injury, and the improvement of the impact performance of vehicle interiors and other safety improvements.[11,12] Preservation of sight in occupants involved in vehicle crashes is expected to continue to improve with the implementation of air bag restraint in the automotive fleet, since crash survivors without closed head injury or facial trauma would be more likely to have intact visual function.

CONCLUSION

Injuries of the eye and periorbital region are occurring in road traffic crashes in which the mechanism of injury appears to be an interaction between the deployment energy of the air bag and the structure of the eye. With the state of current technology, injury to the ocular structures would appear to be an inevitable consequence of air bag deployment since the potential exists for the eye to be exposed to the necessary energy for proper and

adequate deployment of an inflatable restraint, and the disparity between the amount of energy required to restrain an occupant in relation to the threshold energy for eye injury. The incidence of air bag related eye injury may be reduced by decreasing the likelihood for deployment with out-of-position occupants in which the face or eye is in close proximity to the air bag module, and efforts to minimize the potential for objects to become interposed between module and occupant.

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Simula's Line of Inflatable Restraint Technologies

Anita Grierson
Simula Technologies, Inc.
Phoenix, Arizona

Don Dutton
Simula Safety Systems, Inc.
Tempe, Arizona

ABSTRACT

Simula, Inc., currently offers a full line of inflatable restraint technologies designed to meet the safety needs of the automotive, truck, military ground vehicle, and military aviation communities. Simula's Inflatable Tubular Structure (ITS®) provides side-impact and rollover head protection for current-model commercial automobiles, and is being adapted to provide side-impact protection for occupants of the U.S. Army's OH-58D helicopter. Benefits of the ITS technology include the provision of a structural barrier to prevent the occupant's head or torso from striking, or being propelled out of, the vehicle's side window, even when the window has been removed. It also protects a wide range of occupant sizes, deploys in a non-aggressive manner beside the occupant, and has an extended inflation time for occupant protection in multiple-impact scenarios. Simula's Inflatable Tubular Torso Restraint (ITTR®) inflates from the shoulder harness portion of a 3- or 5-point restraint system. The benefits of the ITTR include substantially decreased head translation and rotation in both forward and lateral crashes, and increased distribution of chest loads as compared to conventional restraints. Additional Simula inflatable restraint technologies include the Inflatable Tubular Bolster (ITB) for lower extremity protection, the Inflatable Tubular Cushion (ITC) for side or oblique impact torso protection, and conventional frontal air bags for occupant head and torso protection. Simula is able to combine its full line of inflatable restraint systems with each other and with traditional safety systems such as energy-absorbing seating to enhance protection for all major body areas in a wide variety of crash scenarios.

INTRODUCTION

Simula's experience with inflatable restraints began in the 1980's with the development and qualification of the Inflatable Body and Head Restraint System (IBAHRS) and the development of the Joint Cockpit Air Bag System (JCABS)[1,2,3]. Both of these systems were designed to provide protection against head and torso strikes in helicopter cockpits.

Considered improvements to the IBAHRS systems led to the development of the Inflatable Tubular Structure (ITS) (Figure 1). The ITS technology was patented in 1994, and, following extensive development, entered serial production in 1997, when it

appeared in BMW's 7-Series automobiles. Production and sales of the ITS system currently exceed one million units annually, with aggressive growth planned over the next few years. The ITS technology has been selected for use in 19 current and future automotive platforms. In addition, the ITS is a dual-use technology, and is currently being tailored to provide lateral head protection and head flail mitigation in the U.S. Army's OH-58D Kiowa Warrior CABS.

The fundamental technology used in the ITS is being applied in a variety of other inflatable restraint systems. These include the Inflatable Tubular Torso Restraint (ITTR), the Advanced Head Protection System (AHPS), the Inflatable Tubular Cushions (ITC), and the Inflatable Tubular Bolsters (ITB). Each of these systems is discussed in the following paragraphs.

®ITS and ITTR are registered trademarks of Simula, Inc.

Figure 1.
Simula's Inflatable Tubular System deployed in a BMW.

THEORY OF OPERATION

All products using the ITS technology take advantage of two fundamental elements: an internal inflatable bladder and a braided fabric cover. The braided fabric cover is the key to the functionality of the ITS, and is composed of an integral tube of interwoven helical fibers. As the bladder inflates and increases in diameter, the fibers in the braided fabric cover are reoriented while being pulled over the increasing circumference. This decreases the effective length of the ITS (Figure 2). When the ITS is anchored at each end, the tendency for the braided cover to reduce in length results in a tension across the ITS. The tension acts to pull the ITS into position, and provides a self-supporting barrier to enable the ITS to perform its intended function. These two features distinguish the ITS

from traditional air bag systems. The ITS and its variants also deploy in a non-aggressive manner, reducing many of the out-of-position performance concerns caused by traditional air bag systems.

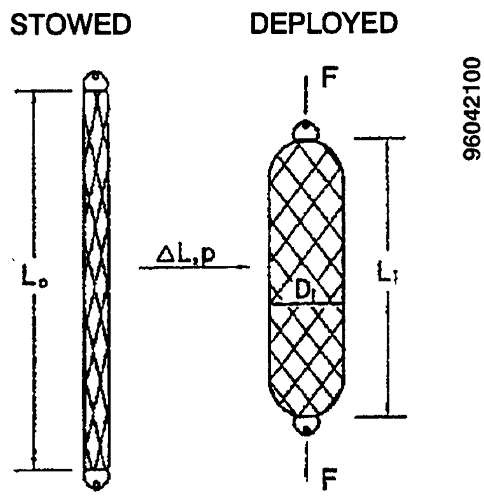

Figure 2.
Simula's Inflatable Tubular Structure - principle of operation.

Inflatable Tubular Structure

The ITS technology was originally introduced in the 1997 BMW 7-Series sedan as a means to mitigate head, neck, and spinal injuries from side and oblique impact collisions. Stowed in the vehicle's roof liner above the door, the deployment of the ITS is initiated upon detection of a lateral crash event. Within 30 msec, the ITS is positioned across both the driver- and passenger-side windows. In tests conducted by the Insurance Institute for Highway Safety, the ITS has demonstrated significant protection against head and neck injuries (Figure 3).

The ITS has also been designed to remain inflated and in position for an extended period of time, providing additional occupant restraint in rollover and secondary crashes. The effectiveness of the ITS has been demonstrated in real-world crashes. In one incident, a 1999 BMW was impacted by several large pick-up trucks at highway speeds, completely totaling the vehicle. The driver survived the impact and is now fully recovered.

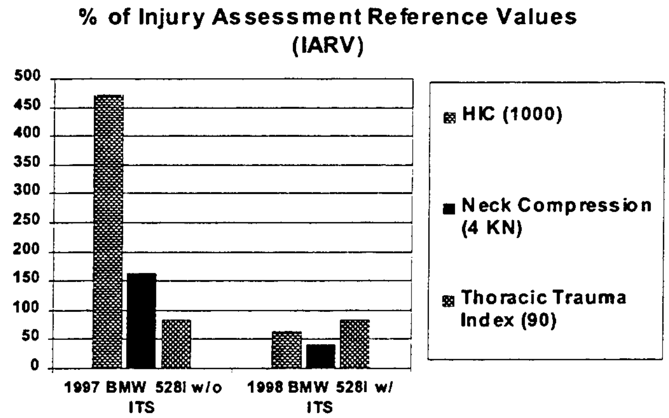

Figure 3.
Insurance Institute for Highway Safety test results[4].

Advanced Head Protection System

Building on the baseline ITS system, the Advanced Head Protection System (AHPS) takes the concept one step further. The AHPS system offers all of the functionality and advantages of the ITS and adds a tensioned fabric shield which envelops the ITS during deployment (Figure 4). In automobiles, the AHPS can span the length of the passenger compartment from the A pillar to the C pillar, providing head and neck protection for both front and rear seat occupants. In the stowed condition, the AHPS system and the ITS can be stored in the door frame or underneath the vehicle headliner (Figure 5).

Inflatable Tubular Torso Restraint

Another variant of the ITS technology is the Inflatable Tubular Torso Restraint (ITTR) system (Figure 6), which Simula is currently developing for automotive, heavy truck, and military ground vehicle applications. The same ITS technology is applied to the shoulder strap(s) of a conventional webbing restraint system. When deployed, the ITTR offers head, neck, and torso protection in frontal, lateral, and rollover crashes. The ITTR's inflated diameter distributes crash forces over a larger area of the occupant's torso than conventional restraints. This distributed load reduces the potential for chest injury. The large diameter of the ITTR also provides essential support to the occupant's head and neck, reducing the injury potential from inertial loading, reducing head flail and the associated risk of head strike, and providing cushioning against items intruding into the cockpit area. Like the ITS unit, the ITTR stays inflated for an extended period of time, securing the occupant against multiple impacts and extended crash events. An additional benefit of the ITTR system is that a pre-tensioning device may no longer be required. A standard pre-tensioner may provide 2-3 inches of stroke while the ITTR can provide 4 inches or more. The ITTR provides shortening along the length of the restraint in a less aggressive manner than the pre-tensioner which pulls webbing from one end. The ITTR can be inflated through the restraint buckle or through the D-ring at the top of the restraint. It will function well whether the restraint is integrated into the seat or mounted to the vehicle.

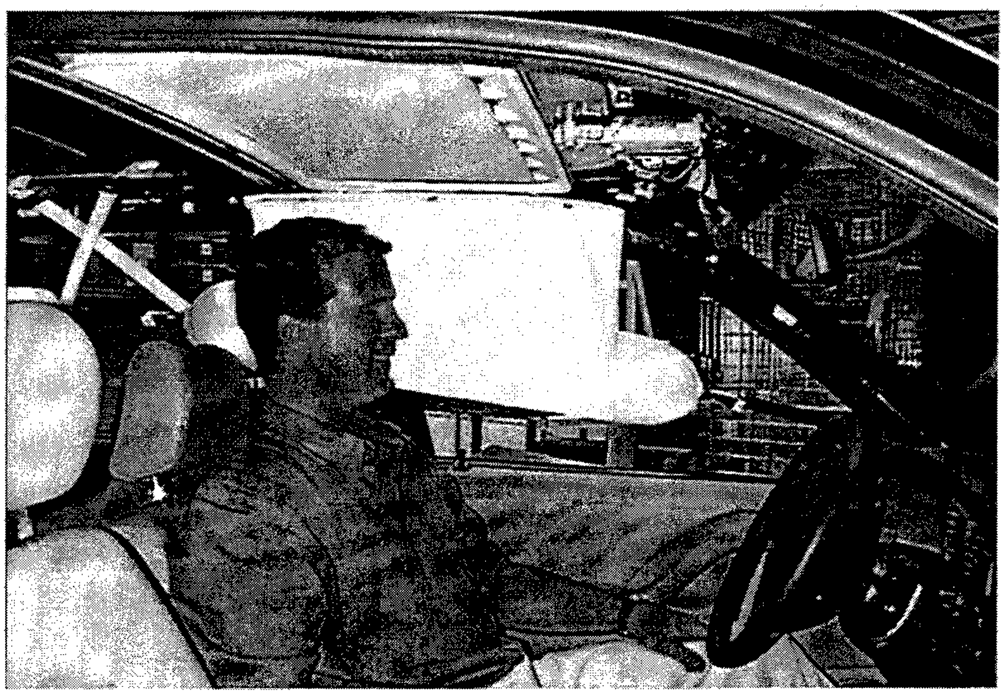

Figure 4.
Simula's Advanced Head Protection System.

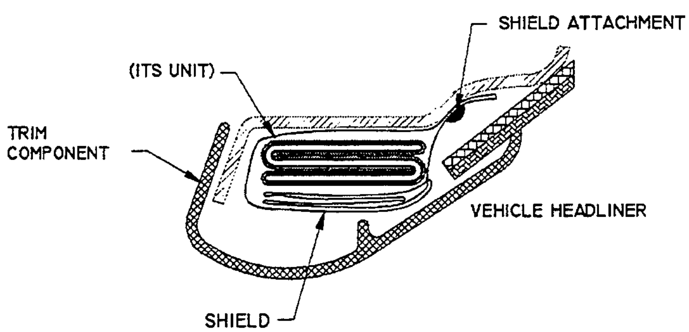

Figure 5.
Simula's Advanced Head Protection System vehicle trim packaging.

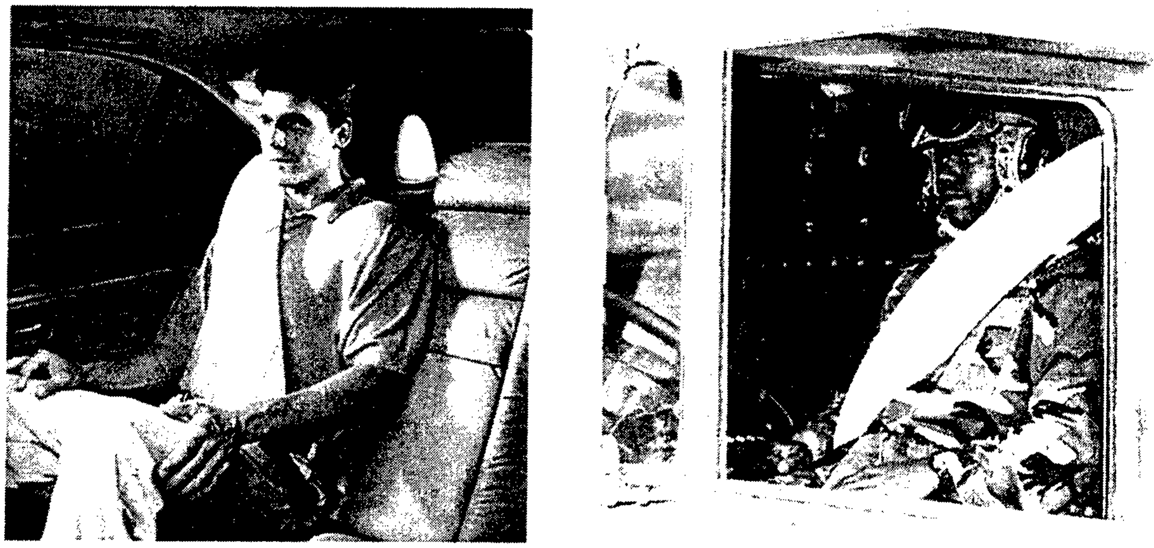

Figure 6.
Simula's Inflatable Tubular Torso Restraint system mounted in an automobile and in a Heavy Tactical Vehicle.

The National Highway Traffic Safety Administration (NHTSA) has conducted rollover and frontal impact testing that has demonstrated the effectiveness of the ITTR system[5]. In a rollover test fixture, the ITTR's performance was compared to standard restraints, seat-integrated restraints, and a seat-integrated restraint with a pre-tensioner. The ITTR system substantially reduced head excursions over the other configurations (Table 1).

Table 1.
NHTSA Rollover Test Results

Restraint System	Head Excursion (cm)
Baseline	12-15
Integrated Seat	9-12
Integrated Seat with Pre-tensioner	8-9
ITTR	3-6

In a 1996 frontal impact test study, conducted with a Hybrid II ATD in an automotive seat, the performance of the ITTR was compared with the NHTSA air belt system, which consisted of a standard air bag mounted onto a webbing restraint system[6]. The air belt was a similar diameter as the inflated ITTR, and the same type of gas generator was used for each test. The ITTR demonstrated substantially reduced head excursion over the air belt and over conventional restraints (Figure 7).

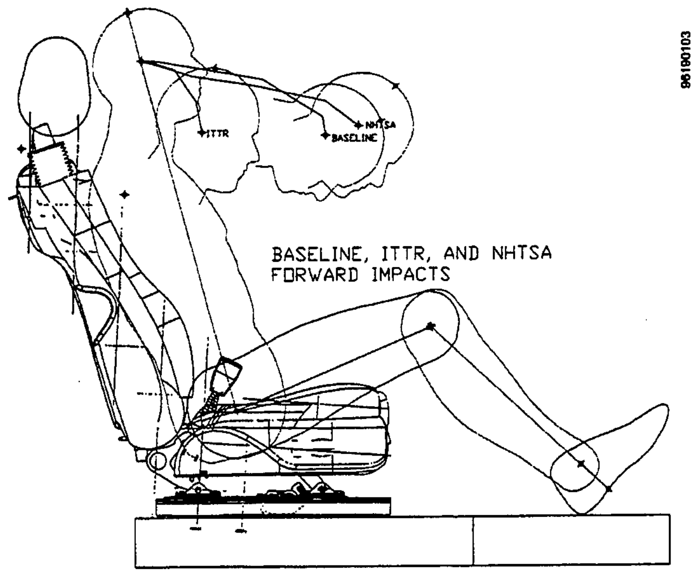

Figure 7.
National Highway Traffic Safety Administration Inflatable Tubular Torso Restraint head flail diagram.

Recently, the ITTR system has been tested in military Heavy Tactical Vehicles[7]. In frontal impact testing, conducted at a 36-G peak deceleration with a 16.7-ft/sec velocity change, the ITTR substantially reduced head flail and chest acceleration over conventional 3- and 4-point restraints (Figure 8, Table 2). In rollover simulation testing, the ITTR also significantly reduced head excursion, preventing head strikes on the roof of the cab (Figure 9, Table 2).

3-point restraint

4-point restraint

ITTR

Figure 8.
Forward impact in a military heavy truck.

3-point restraint

4-point restraint

ITTR

Figure 9.
Rollover simulation in a military heavy truck.

Table 2.
Frontal and Rollover impact test results

Restraint	Frontal Impact Head Displacement (in.)	Frontal Impact Chest Acceleration (Gx)	Rollover Head Displacement (in.)	Rollover Roof Strike
3-point	13.2	13.9	9.5	Yes
4-point	13.1	16.9	8.1	Yes
ITTR	6.9	12.1	4.9	No

ADDITIONAL PRODUCTS USING ITS TECHNOLOGY

The ITS technology is being considered for a variety of other inflatable safety systems. The Inflatable Tubular Cushion (ITC), shown in Figure 10, has been evaluated as a means to provide occupant lateral restraint in a number of applications from automobiles, to ejection seats, to side-facing aircraft seats. The ITC deploys either one or two inflatable cushions that protect the occupant's torso and pelvic areas. Mounted appropriately, the ITC may also provide protection from limb flail during aircraft ejection events.

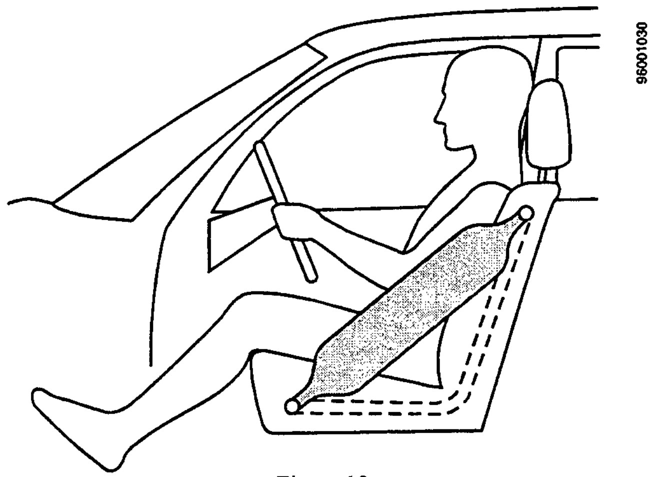

Figure 10.
Illustration of Simula's Inflatable Tubular Cushion.

In a further iteration of the ITS, Inflatable Tubular Bolsters (ITB) may be positioned under dashboards or instrument panels to reduce lower torso movement and leg flail and mitigate torso, knee, and leg injuries that may result from frontal crashes (Figure 11). By limiting the forward motion of the lower extremities, the ITB may help to prevent submarining, as well as preventing entrapment of the feet in the vehicle's footwell. In each of these applications, the ITS technology offers significant benefits over traditional air bag systems in terms of extended inflation duration and self-supporting structure.

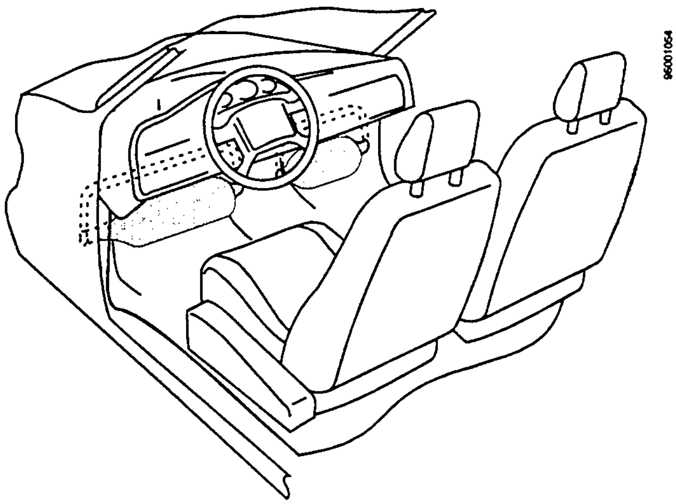

Figure 11.
Illustration of Simula's Inflatable Tubular Bolster.

CONCLUSION

Simula's line of inflatable restraint technologies, from the helicopter CABS to the ITS and its variants, meets the occupant protection needs for the full range of impact scenarios and transportation modes. With its unique capabilities, the ITS technology can provide both a non-aggressive alternative to conventional restraint systems and an additional restraint mechanism which design engineers can use to optimize vehicle occupant protection.

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The Inflatabelt™ Occupant Restraint System[1]

Lowell W. Roemke
BFGoodrich Aerospace
Safety Systems Division
Aircraft Evacuation Systems
3420 South 7th Street
Phoenix, Arizona 85040

ABSTRACT

Showing compliance with the head impact protection requirements found in the Seat Dynamic Performance Standards defined in 14 CFR Part 25, §25.562 has proven to be a challenging task. Those standards define a prescribed set of impact conditions and require that each occupant must be protected from serious head injury where head contact with seat or other structure can occur. A number of means have been used to provide head impact protection, among those being: the elimination of the head strike hazard, the use of occupant upper torso restraints, the installation of bulkhead mounted airbags, and the addition of energy absorbing materials. A new inflatable restraint system has now been developed that, unlike an automotive-style airbag, acts as a cushioning barrier between the occupant and the fixed object during the impact event. The Federal Aviation Administration (FAA) has determined that Special Conditions are necessary to certify the new/novel restraint system. The design, testing, and certification of that new restraint system are the subjects of this paper.

INTRODUCTION

Aircraft Seat Crashworthiness Standards have been evolving for 50 years as shown on Figure 1. In the 50's, the seats were required to withstand 9g's. FAA studied 933 worldwide jet transport accidents that occurred between 1959 & 1979. Of the 933, 176 survivable accidents received detailed analysis. One of the things learned was that if seats could be kept in their tracks, survivability greatly increased. Thus, FAA has now required 16g seat standards for newly certified aircraft and has drafted a 16g retrofit rule, which is expected to issue in the near future. The 16g rule includes Head Injury Criteria (HIC) in addition to seat structural requirements.

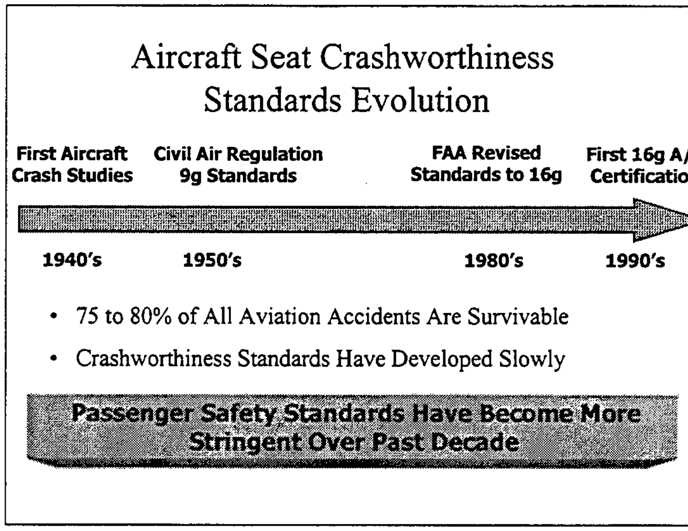

Figure 1

Seat manufacturers have responded to the regulations by developing 16g compatible and 16g compliant seats. It is questionable if many 16g compatible seats developed prior to the 16g retrofit rule issuance will comply with the data documentation the rule will now require.

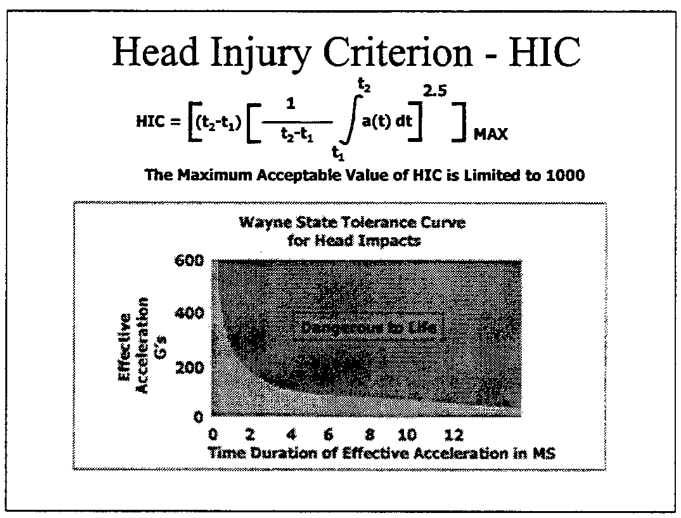

Figure 2

The toughest injury criterion to meet is HIC. This equation on Figure 2 shows how the Head Injury Criterion or HIC is calculated. It is the same measure used in the Federal Motor Vehicle Safety Standards #208. Its value is calculated as an integration of the head acceleration over time upon contact with

structure. The maximum value of HIC allowed in aircraft and motor vehicles is 1000. It is my understanding that, statistically, a normal person may sustain a HIC of 1000 or less and escape life threatening head injury. A person is incapable of surviving exposure to very high g forces if the time duration of the exposure is more than a few milliseconds as shown in this Wayne State chart on Figure 2.

The common way of meeting HIC requirements with a standard seat belt is to move the seats back from bulkheads or aircraft structure. Seat manufacturers have developed other methods that offer some HIC performance improvement but not without weight or space penalties. Articulating seat pans, break-away seat backs and bulkhead-mounted airbags are examples of these methods. All of these methods require some setback from the bulkhead to meet HIC requirements, which may lead to loss of revenue seats. One large commercial operator has estimated that up to 5000 seats could be lost in their fleet if their only option is to move seats back from the bulkheads.

THE INFLATABELT™ RESTRAINT SYSTEM

We believe that the Inflatabelt™ Restraint System offers a better solution to the problem as shown in Figure 3. It has a familiar non-intrusive appearance similar to a standard lapbelt. Upon activation of the system during a crash event, the Inflatabelt™ restraint system deploys an airbag between the occupant and the lapbelt which pretensions the belt, and restricts the forward motion of the head and chest. The airbag then deflates rapidly to enable egress.

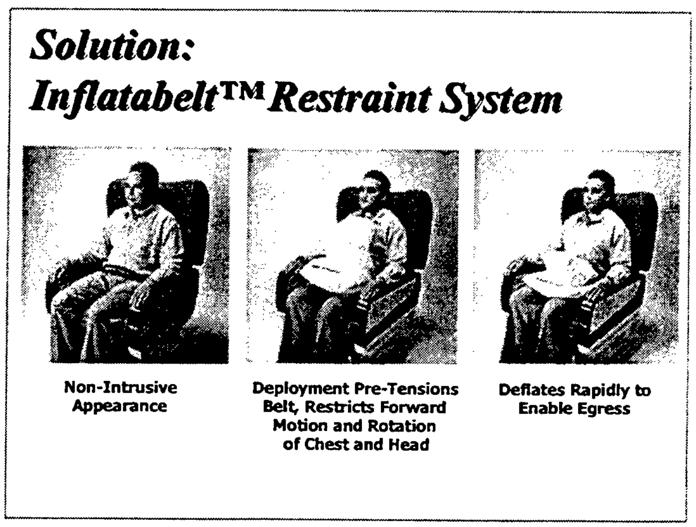

Figure 3

Our goal is to provide a seat belt that looks similar to an ordinary accepted automotive seat belt. It is retrofitable to existing seats so it won't require redesign of the seat interface. The system provides its own power supply and is not dependent on aircraft power. The design philosophy for the Inflatabelt™ restraint system is to first pretension the belt to keep the occupant from sliding forward. With a standard "tight" seatbelt, the occupant may slide forward 6-8 inches before the belt restrains him. The Inflatabelt system takes up all the slack in the belt and actually moves the occupant back and down into the seat before he has moved from the g forces. The load is distributed over the chest and thighs, not just a 2-inch wide belt area. The airbag absorbs the energy of the occupant going into the bag, reducing the forward motion of the chest and head and eliminates bulkhead contact.

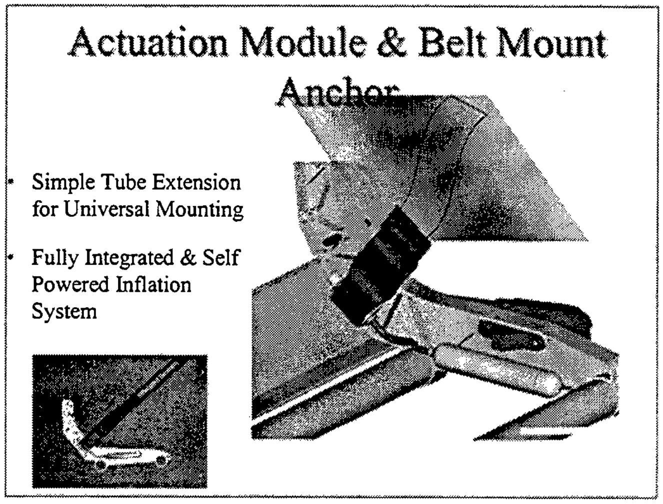

Figure 4

The Inflatabelt™ restraint system attaches to a typical seat at the normal lapbelt anchor point and to the seat spreader as shown on Figure 4. The heart of the Inflatabelt™ restraint system is the Direct-Thermal™ inflator or DTI™ as shown in Figure 5. This inflator provides cool gas to the air bag, so cool that air bag fabric temperature remains within a few degrees of ambient cabin temperature. The gas produced is non-toxic and contains very little particulates. The bags small size allows for configuration flexibility and ease of adapting to various seat platforms.

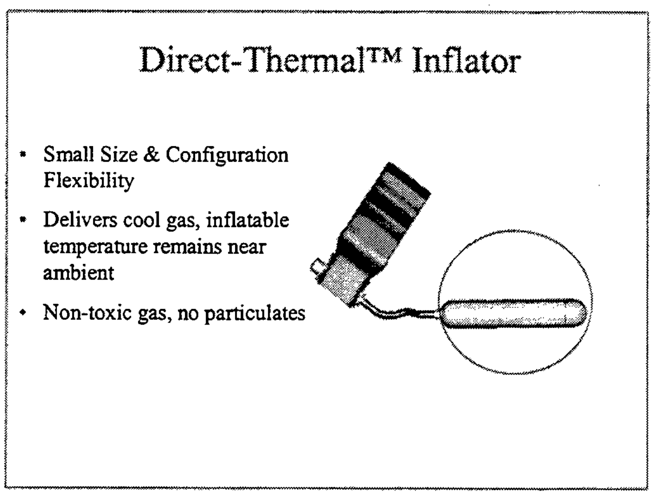

Figure 5

The firing system is mounted at the end of the inflator as shown on Figure 6 and deploys the Inflatabelt™ restraint system airbag upon sensing a crash acceleration threshold. The system is not activated when exposed to turbulence, vibration or rejected take-off thresholds. The system has a self-contained battery and does not require aircraft power. The system is not armed until installed on the seat. The entire firing system is contained in a Faraday shield making it immune to external Radio Frequency (RF) energy.

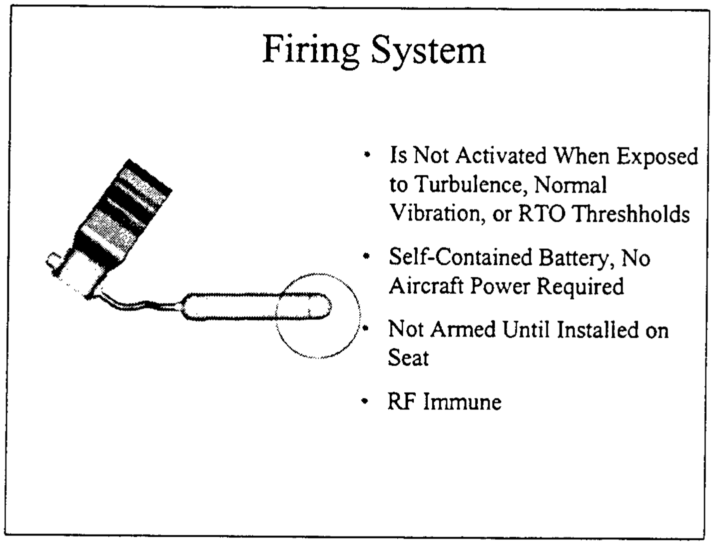

Figure 6

The Inflatabelt™ restraint system contains a small airbag within the deployment module. The airbag is folded very precisely and placed inside tubular webbing. When gas from the inflator enters the airbag, the airbag ruptures a weak link in the tubular webbing and deploys into the correct position on the occupant. The inflatable airbag is constructed from thin lightweight, flexible coated fabrics shown as on Figure 7. It is vented to provide deflation and reduce rebound. The materials used in the construction comply with the environmental requirements for cabin interiors.

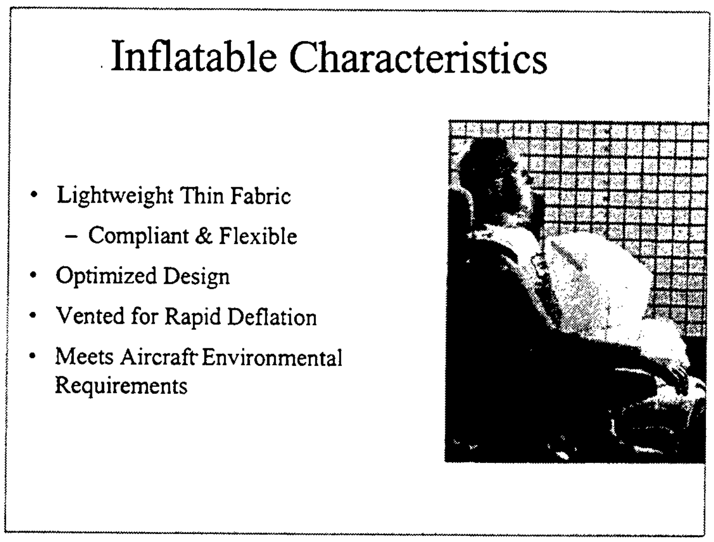

Figure 7

MODELING

At BFGoodrich Aerospace, we make extensive use of simulation and modeling programs. For modeling we use MADYMO. Finite Element models of the seat are used to simulate seat dynamics. It provides a full range of validated occupant models from small to large. It is also compatible with Computational Fluid Dynamic models. The next three illustrations, Figures 8, 9 and 10, depict the modeling of a 16g crash event with 2 different restraint systems.

Figure 8 compares MADYMO models of a standard lapbelt and an Inflatabelt™ restraint system. The entire FAA 16g crash test takes only 180 milliseconds. The peak g occurs at 90 ms into the event. At 20

milliseconds, the occupants have not yet felt the effect of the de-acceleration or moved appreciably in their seats. The Inflatabelt™ restraint system has not yet been activated but is close to activation.

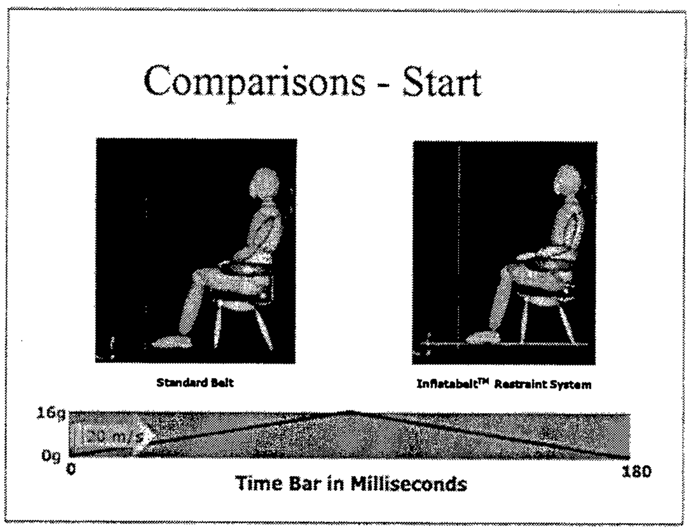

Figure 8

At 80 milliseconds as shown on Figure 9, the crash event is nearly half over. The occupant in the standard lapbelt is just beginning to be restrained. This occupant has slammed forward approximately six inches taking up the slack and stretch of the standard lapbelt and placing high loads on the seat belt attachment points. The Inflatabelt™ Restraint System has fully deployed the airbag between the seat belt and the occupant before the occupant has moved in relation to the seat. This pre-tensioning of the seat belt actually presses the occupant back and down into the seat. The pre-tensioning of the seat belt applies the seat belt load to the seat attachment points sooner and reduces the peak load applied to the seat by about 20%.

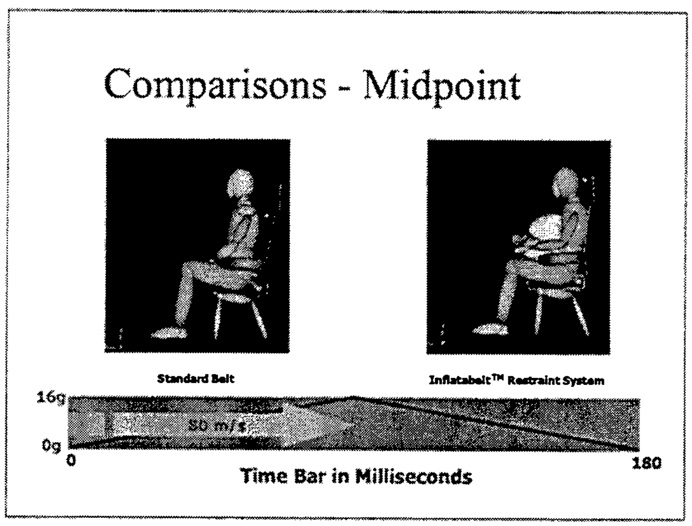

Figure 9

At 150 milliseconds, nearing the end of the crash event as shown on Figure 10, the occupant in the standard lapbelt has struck his head on the bulkhead. In this model, the bulkhead is located at 35 inches from the seat reference point (SRP). HIC level would be quite high resulting in serious injury, unconsciousness or death. The Inflatabelt™ restraint system has restrained the occupant by distributing the crash loads over a

wide area of the chest and thighs. The head has not contacted any aircraft structure and has stopped short of the bulkhead by 10-12 inches. This occupant would be conscious and capable of evacuating the aircraft.

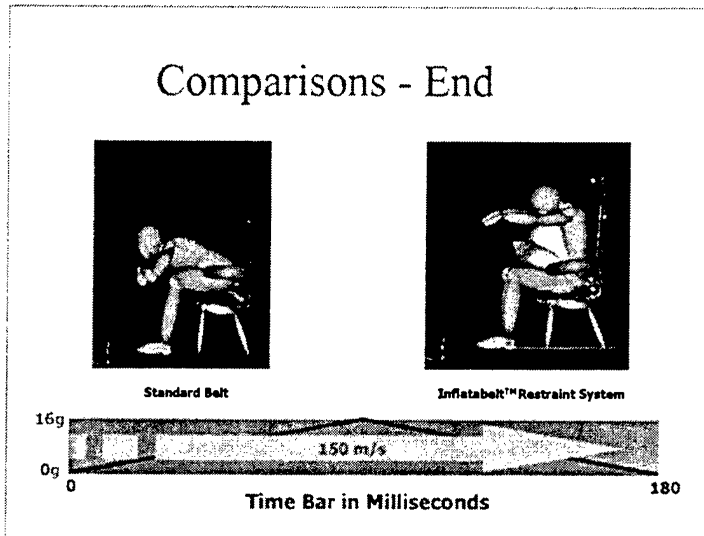

Figure 10

DYNAMIC SLED TESTING

In addition to modeling, of course we have conducted 16g dynamic sled tests. Figures 11, 12, and 13 show various views of a 16g dynamic sled test. In this test, a direct comparison of the occupant protection performance of standard seat belt restraints and Inflatabelt™ restraint systems was conducted. Two sets of double seats were mounted on a sled. The double seats on the right side of the sled were equipped with standard seat belts. The double seats on the left side of the sled were equipped with Inflatabelt™ restraint systems. Four 50th percentile Hybrid II Anthropomorphic Test Devices (ATDs) were placed in the seats. An open frame was positioned in front of the seat to represent the plane of a bulkhead at a distance of 35 inches from the seat reference point.

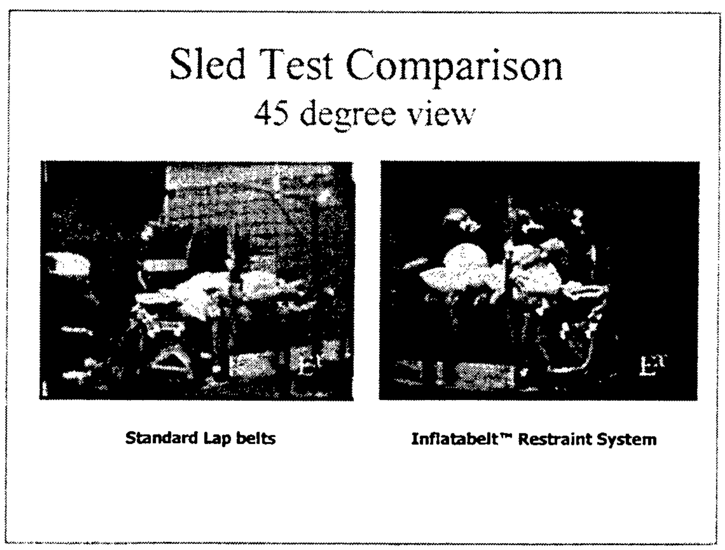

Figure 11

Figure 11 shows camera views of the 16g dynamic sled test from a 45-degree position at the point of the most forward rotation of the ATDs. In this view, it is seen that the ATDs with standard seat belts have rotated forward and that their heads have passed through the bulkhead plane by approximately 4-inches. It can also be seen that the ATD on the right with the standard seat belt has pitched forward with such force that when its chest contacted its knees, the force was enough to drive the legs down breaking a ¾-inch plywood floorboard. By contrast, the ATDs on the left side of the sled with the Inflatabelt™ restraint system have been restrained more effectively, with approximately 12 inches of clearance between their heads and the bulkhead plane and the floorboard remained intact.

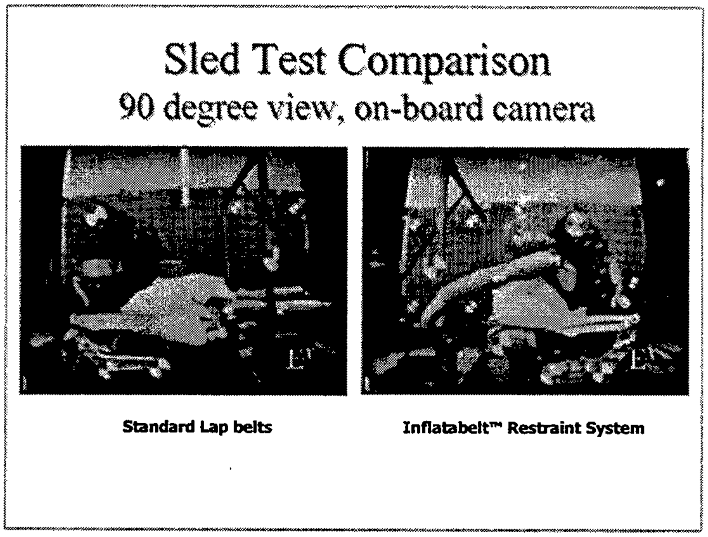

Figure 12

Figure 12 shows views of the same 16g dynamic sled test from on-board cameras mounted at 90-degrees to the sled. The pre-tensioning action provided by the Inflatabelt™ restraint system has held the ATDs' pelvis well back in the seat. By contrast, the ATDs with standard seat belts have slid forward in their seats.

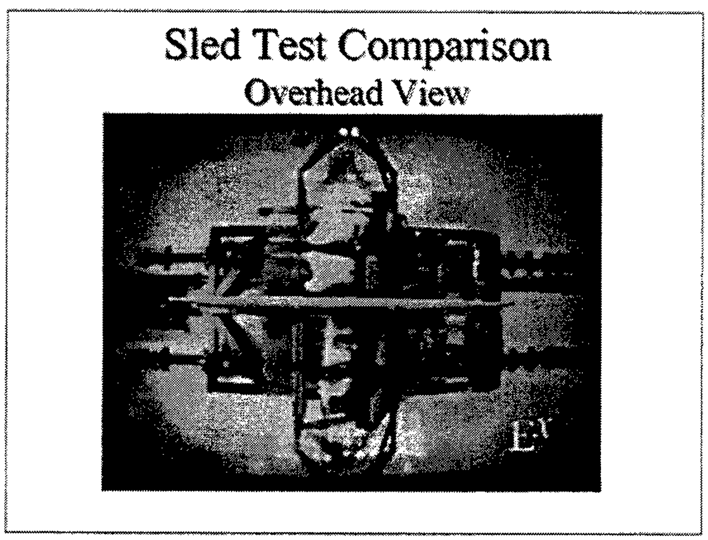

Figure 13

Figure 13 shows the overhead camera view of the 16g dynamic sled test. This view shows both seats, directly illustrating the comparison of Inflatabelt™ restraint system performance to standard seat belts. It clearly shows how far the heads of the occupants with standard lapbelts have passed through the plane of the bulkhead frame. The heads of the occupants with the Inflatabelt restraint systems have stopped well back from the bulkhead.

TEST RESULTS

Many restraint system performance parameters were measured during the tests discussed above. Some of these included ADT trajectories, seat belt loads, seat mounting loads and Head Injury Criterion. A comparison of the trajectories of the head, shoulder and knee are shown in Figure 14. Note that the head target is located approximately 4-inches below the top of the head. The head target path of the ATDs with the standard seat belt shows that head contact with the bulkhead would have occurred resulting in severe injury or death to the occupant.

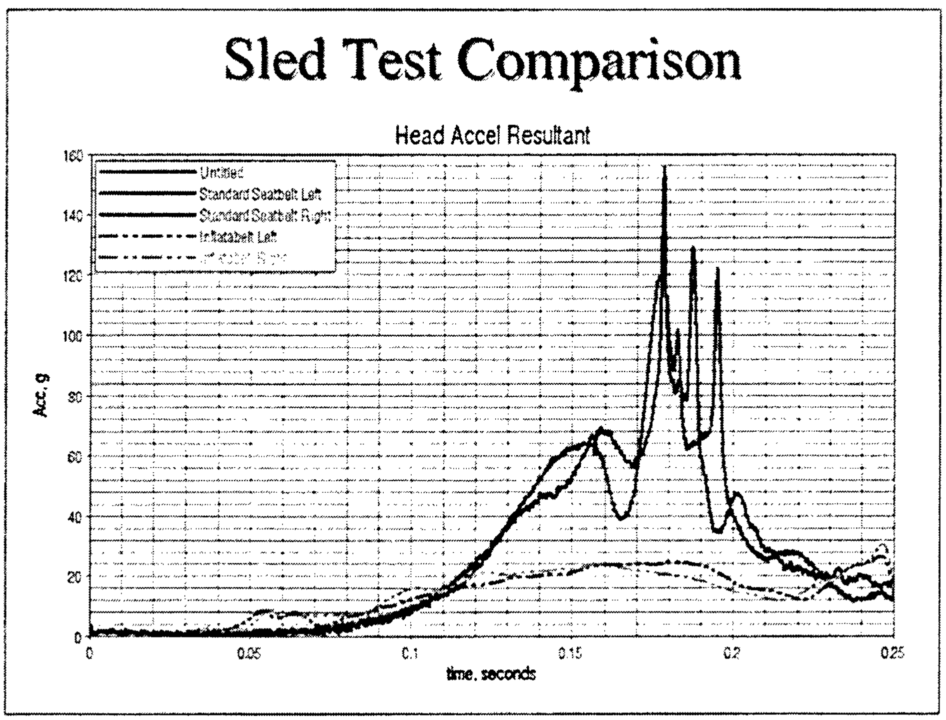

Figure 14

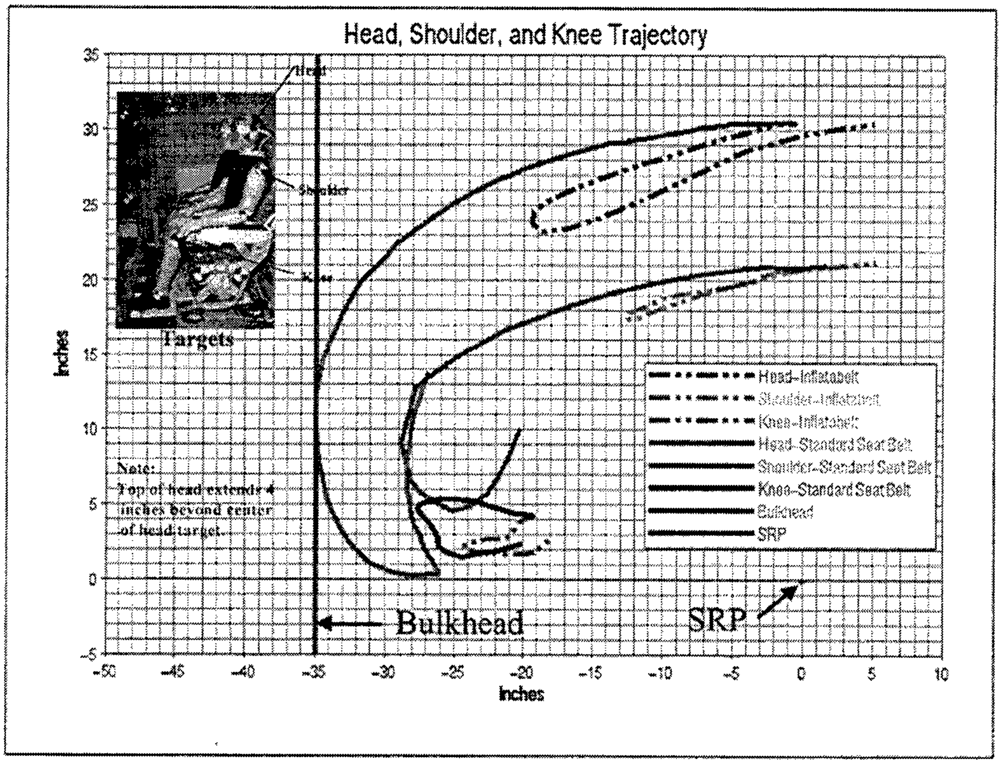

Figure 15

Even though there was no contact with an actual bulkhead in this dynamic test, the ATDs with standard seat belts experienced very high acceleration forces. The ATDs with the Inflatabelt™ restraint system received very safe and acceptably low acceleration forces as shown in Figure 15. The HIC obtained in this test was over 2100 for the ATDs with standard seat belts and below 400 for the ATDs with Inflatabelt restraints.

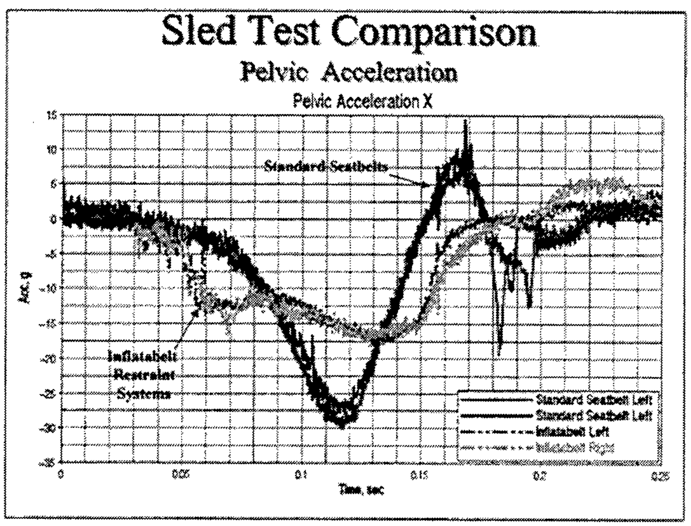

Figure 16

Pelvic acceleration is also greatly reduced by the Inflatabelt™ restraint system as shown on Figure 16, with peak values about 50 percent less than that experienced by an occupant with a standard seat belt. The Inflatabelt™ restraint system also reduces the loads on the seat and aircraft floor structure. Figure 17

illustrates a comparison of the loads applied to the seat belt attachment points. Pre-tensioning provided by the Inflatabelt™ restraint system prevents the occupant's pelvis from sliding forward thereby reducing peak belt load.

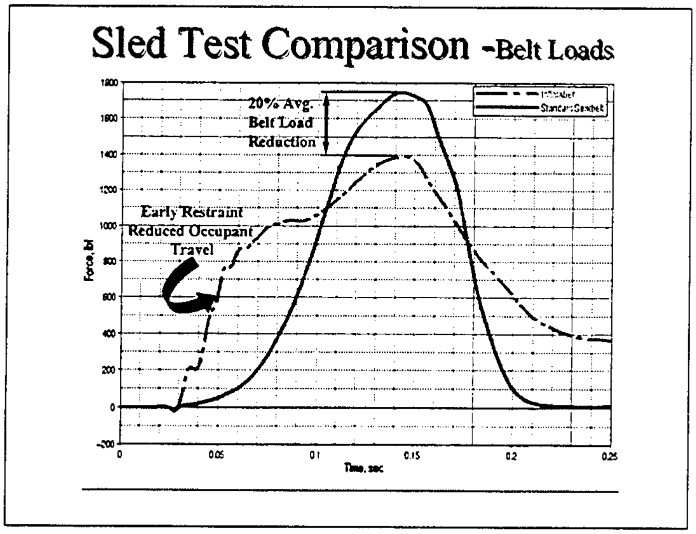

Figure 17

As a result of reducing the loads applied to the seat's belt attachment points and seat leg structure by the Inflatabelt™ restraint systems, the load transferred into the floor structure is also reduced significantly. Figures 18 and 19 illustrate the load reduction in the longitudinal and vertical directions.

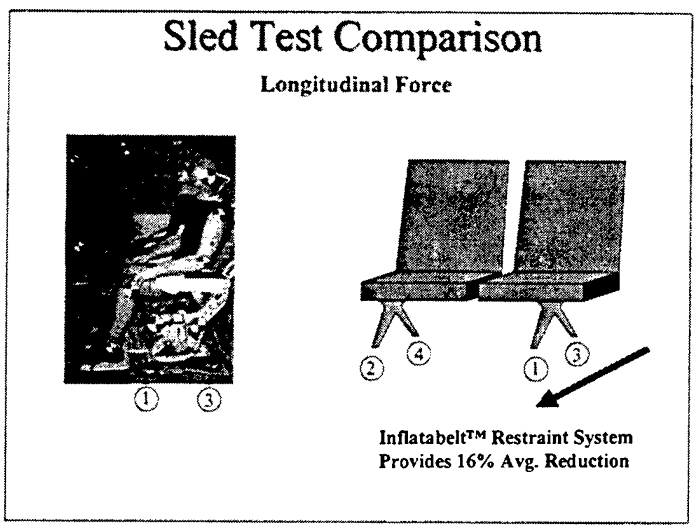

Figure 18

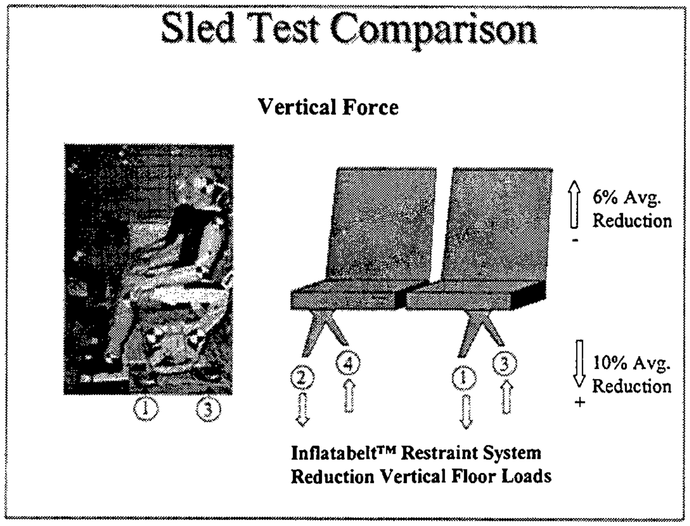

Figure 19

It is important to recognize that 16g dynamic tests do not test the aircraft floor beam structure. Some seat manufacturers have increased the number of seat track plunger attachments on the rear legs of their seats to achieve compliance with 14CFR Part 25, §25.562. While this may allow a seat to become certified, it does nothing to reduce the loads the seat puts into the floor structure. When retrofitting seats into an aircraft, the ability of the floor beams to carry increased load should be taken into account. The Inflatabelt™ restraint system reduced resultant floor loads an average of 12 percent in this test as compared to a standard seat belt.

CERTIFICATION STANDARDS, SPECIAL CONDITIONS

An application for a Supplement Type Certificate (STC) for the installation of an inflatable airbag-seatbelt for the front row passengers' seats in the Boeing Model 777-200, and 300 series airplane has been submitted to the Federal Aviation Administration (FAA). The FAA determined that current Part 25 airworthiness regulations do not contain adequate or appropriate safety standards necessary to certify the new/novel occupant restraint system with an integrated inflatable airbag device. Therefore, in addition to the requirements of 14 CFR Part 25, §25.562 and 25.785, additional safety standards, special conditions, are necessary to establish a level of safety equivalent to that established by the airworthiness standards for transport category airplanes.

The FAA has considered the installation of airbag devices on aircraft to have two primary safety concerns: (1) that they perform properly under foreseeable operating conditions, and (2) that they do not perform in a manner or at such times as would constitute a hazard to the airplane or occupants.

The proposed special conditions address these safety concerns by establishing performance standards applicable to the inflatable airbag-seatbelt. In summary these proposed special conditions require that the inflatable lapbelt deploy and provide occupant impact protection at aircraft crash conditions where it is necessary to prevent serious head injury. Conversely the inflatable should not deploy during minor impacts and thus not be available should a later severe impact condition occur. The inflatable lapbelt needs to provide impact protection for all seat occupants, thus the means of protection must consider a range of stature from a two-year-old child to a ninety-fifth percentile male. Other occupant related performance standards address the number and placement of seated and other occupants, incorrectly worn or installed inflatable lapbelts, emergency egress issues, and potential hazards associated with fire, gas and particulate matter.

The proposed special conditions include performance standards concerning the aircraft's safe continued operation after an inadvertent inflatable lapbelt deployment. Inflatabelt system reliability standards have also been defined to ensure the integrity of the inflatable lapbelt activation system and its proper function after loss of normal aircraft electrical power and/or a fuselage transverse separation.

The complete text of the proposed special conditions can be found in the Appendix. The procedural requirements for the issuance of special conditions can be found in 14 CFR Part 11, §11.28 and 14 CFR Part 21, § 21.16.

ACKNOWLEDGEMENTS

1. Stephen J. Soltis
   Federal Aviation Administration, Los Angeles Aircraft Certification Office

2. Federal Aviation Administration
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3. Tracy Ton
   Federal Aviation Administration, Los Angeles Aircraft Certification Office

4. BFGoodrich Aerospace
   Universal Propulsion Company, Phoenix

5. BFGoodrich Aerospace
   Aircraft Evacuation Systems, Phoenix

6. Exponent™, Failure Analysis Associates©, Phoenix

APPENDIX

Proposed Special Conditions

The inflatable seat belt program will contain special conditions as part of the Certification Basis. The following is a list of the draft special conditions.

1. It must be shown that the inflatable lapbelt will deploy and provide protection under crash conditions where it is necessary to prevent serious head injury. The means of protection must take into consideration a range of stature from a two-year-old child to a ninety-fifth percentile male. The inflatable-lapbelt must provide a consistent level of energy absorption throughout that range. The following situations must be considered:

   a. The seat occupant is holding an infant,
   b. The seat occupant is a child in a child restraint device,
   c. The seat occupant is a child not using a child restraint device,
   d. The seat occupant is a pregnant woman.

2. The inflatable lapbelt must provide adequate protection for each occupant regardless of the number of occupants of the seat assembly, considering that unoccupied seats may have buckled or unbuckled seatbelts.

3. The design must prevent the inflatable lapbelt from being incorrectly buckled and/or incorrectly installed such that the airbag would not properly deploy. Alternatively, it must be shown that such deployment is not hazardous to the occupant, and will provide the required head injury protection.

4. It must be shown that the inflatable lapbelt system is not susceptible to inadvertent deployment as a result of wear and tear, or inertial loads resulting from in-flight or ground maneuvers (including gusts

and hard landing), likely to be experienced in service.

5. Deployment of the inflatable lapbelt must not introduce injury mechanisms to the seat occupant, or result in injuries that could impede rapid egress.

6. It must be shown that the inflatable lapbelt will not be a hazard to an occupant who is in the brace position when it deploys.

7. It must be shown that an inadvertent deployment, that could cause injury to a standing or sitting person, is improbable.

8. It must be shown that inadvertent deployment of the inflatable lapbelt, during the most critical part of the flight, will either not cause a hazard to the airplane or is extremely improbable.

9. It must be shown that the inflatable lapbelt will not impede rapid egress of occupants10 seconds after its deployment.

10. The system must be protected from lightning and HIRF. For the purpose of complying with HIRF requirements, the inflatable lapbelt system is considered a "critical system" if its deployment could have a hazardous effect on the airplane; otherwise it is considered an "essential" system.

11. The inflatable lapbelt must function properly after loss of normal aircraft electrical power, and after a transverse separation of the fuselage at the most critical location. A separation at the location of the lapbelt does not have to be considered.

12. It must be shown that the inflatable lapbelt will not release hazardous quantities of gas or particulate matter into the cabin.

13. The inflatable airbag seatbelt installation must be protected from the effects of fire such that no hazard to occupants will result.

14. There must be a means for a crewmember to verify the integrity of the inflatable lapbelt activation system prior to each flight or it must be demonstrated to reliably operate between inspection intervals.

Inadvertent or Unnecessary Deployment of Inflatable Occupant Restraints

Dr. George Sprague
Manager, Integrated Logistics Support and
Configuration Management
Simula Safety Systems, Inc.
Applied Technologies Division
7414 S. Harl Ave.
Tempe, AZ 85283
spragueg@sssi.simula.com

ABSTRACT

The probability of inadvertent or unnecessary deployment of inflatable occupant restraints is of interest to both the military and commercial safety communities. This paper discusses some important issues that should be considered when establishing this system requirement and its effect on safety assessment. Methodologies and techniques for evaluating and improving this numeric are presented with specific references to the Cockpit Air Bag System (CABS) currently under qualification for the U.S. Army Black Hawk and Kiowa Warrior Helicopters. The need for application of standard reliability techniques to both hardware and software designs utilizing modeling, predictions, failure mode and effects, and fault tree analysis are briefly discussed as applicable methodologies for inadvertent or unnecessary deployment probability analysis.

INTRODUCTION

The probability of inadvertent or unplanned deployment of cockpit air bag systems has been a topic of numerous system safety working group meetings. Why should we care? The answer is quite obvious. We must evaluate the risks involved in the introduction of a new system into an operational aircraft. Results of extensive hazard analyses indicate that the potential hazards introduced by an air bag system fall in two general categories: out-of-position risks and operational risks. Out-of-position risks include potential extremity injury to the pilots and injury to maintenance or rescue personnel. Operational risks include impact on controls, the startle effect, visibility impairment, emergency ingress/egress impairment, underwater egress restriction, critical maneuver impacts (nap of the earth (NOE) flight, hover, etc.), visual instrument blockage, night vision degradation, etc. The criticality, probability, and severity of these hazards must be evaluated during development and qualification testing to obtain Airworthiness Release.

The Federal Aviation Administration (FAA) has established stringent requirements for failure probabilities. FAA Advisory Circular No. 25.1309.1A specifies that major failure conditions must be improbable (1×10^{-5} or less but $> 10^{-9}$) and catastrophic failure conditions must be extremely improbable (10^{-9} or less). Based on the following discussion, we will investigate the application of these numerics to inflatable restraint systems.

DISCUSSION

What does the probability of inadvertent or unplanned deployment mean?

The specification requirement is usually stated as a probability of $1X10^{-x}$, where X is 5, 6, 9, etc. Most of us cannot identify with this type of numeric. The reciprocal is generally more meaningful, i.e., one inadvertent deployment in 10^5, 10^6, 10^9, etc. events. However, what is the denominator? It is frequently unspecified. It could be missions, operating hours, flight hours, miles, etc. Assuming that we know the denominator basis, the numeric is still not very meaningful unless we know the operational profile of the airframe or fleet (i.e. number of aircraft in operation and number of missions or flight hours per year). With this information, the probability numeric becomes useful for life-cycle cost evaluations and design trade-off studies. The following example illustrates this process:

Assume: Specification requirement of $1x10^{-5}$ (probability of inadvertent deployment)
2000 aircraft with 2-hr missions each flying 50 mission/yr
10% of inadvertent deployments result in pilot injury

This equates to 100,000 missions/yr or 200,000 flight hr/yr.

Table 1 illustrates various resultant calculations:

Table 1. Inadvertent Air Bag Deployment

Specification Requirement Probability of Inadvertent Deployment	Inadvertent Deployment per Year (Missions)	Years/Inadvertent Deployment (Missions)	Injuries per Year (Missions)	Inadvertent Deployment per Year (Flight Hours)	Years/Inadvertent Deployment (Flight Hours)	Injuries per Year (Flight Hours)
1×10^{-5}	1.0	1	0.1	2	0.5	0.2
1×10^{-6}	0.1	10	0.01	0.2	5	0.02
1×10^{-7}	0.01	100	0.001	0.02	50	0.002
1×10^{-8}	0.001	1,000	0.0001	0.002	500	0.0002
1×10^{-9}	0.0001	10,000	0.00001	0.0002	5000	0.00002

The critical parameter in evaluating the safety risk of inadvertent deployment is the percentage of inadvertent deployments causing injury and the severity of these injuries. Extensive human factors analyses and testing have been conducted and are continuing for the CABS as an integral part of the development and qualification test programs.

How do you analyze the probability of inadvertent deployment?

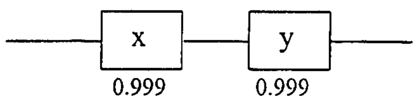
The major contributor to the probability of inadvertent deployment in an inflatable restraint system is the electronic crash sensor unit (ECSU). The ECSU detects the occurrence of impact, decides the severity of the crash, and sends the signal to deploy the air bags. The complexity of these functions requires extensive use of software to accomplish these tasks. Since the software is usually embedded

in the hardware (firmware), the hardware, software, and software/hardware interface must be analyzed to determine the probability of inadvertent deployment.

The following traditional reliability methodology is suggested to predict the inadvertent deployment probability numeric. First, by means of an extensive Failure Mode, Effects and Criticality Analysis (FMECA) and/or a Fault Tree, determine the hardware/software failure modes that could result in inadvertent deployment. Second, assign failure rates to these failure modes and calculate the probability of failure (1-Reliability) associated with inadvertent deployment.

Redundancy is the traditional design approach to increase the reliability of critical circuits identified in the FMECA and/or Fault Tree. The power of redundancy is illustrated by the following example. Assume components x and y each have a reliability of 0.999.

Series Model

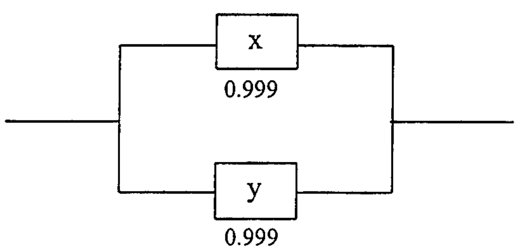


$R_t = R_x \cdot R_y$

$R_t = (0.999)^2 = 0.998$

Probability of Failure $= 1 \times 10^{-3} + 1 \times 10^{-3} = 2 \times 10^{-3}$

Redundant Model



$R_t = R_x + R_y - R_x\ R_y$

$R_t = 2\,(0.999) - (0.999)^2 = 0.999999$

Probability of Failure $= 1 \times 10^{-3} \bullet 1 \times 10^{-3} = 1 \times 10^{-6}$

The application of redundancy in both hardware and software designs can decrease the probability of failure and the probability of inadvertent deployment by many orders of magnitude.

How do we improve the probability of inadvertent deployment?

To reduce the probability of inadvertent deployment from a hardware/software design standpoint, the goal is to eliminate or significantly reduce single point failures. The automotive industry has been concerned with inadvertent deployments for many years. Figure 1, from a 1992 Honda service manual, illustrates the use of both serial and parallel sensors and backup power capabilities for the Supplemental Restraint System (SRS).

The traditional reliability approach is to introduce circuit redundancy; however, this can double or triple electronic components and may require voting schemes. This approach is used in most fly-by-wire systems. To obtain true redundancy, different computer processors and coding should be used in the redundant legs. Fortunately, the use of encryption techniques can be used to simplify ECSU design to obtain dramatic reduction in inadvertent deployment probability with minimal addition of components. This design technique is referred to as a combination lock. By use of the traditional redundancy techniques for the crash sensing function (accelerometers) and firing circuits, and the combination lock for the computer processing functions, the CABS inadvertent deployment probability will be decreased from $2x10^{-6}$ to $2x10^{-12}$ with only a 5% increase in electronic parts. Figure 2 illustrates the major function flow.

As shown in Figure 2, the accelerometers are redundant. A dual circuit is incorporated between the complex programmable logic device (CPLD) and the squib drivers to act as a code sequence lock, locking out all firing energy to the squib drivers, unless the correct dual-deployment code is received (in the proper sequence). Each combination lock circuit acts as a combination lock. It will not enable unless the CPLD sends a specific deploy code. Any hardware failure causing random data to be sent to the combination lock will be recognized as unacceptable, and air bag deployment inhibited. Not only do the valid deployment codes have to be verified, they have to be sent through both combination locks, simultaneously, to activate the air bags. In addition, two separate squib drivers are required to activate an air bag. Single point failure of one driver will not cause deployment. Figure 3 illustrates the operation of the 5-stage software combination lock.

As illustrated previously, the possibility of software causing an inadvertent deployment is essentially eliminated by segmenting the operation required to send deployment codes. To verify inadvertent deployment analyses, extensive software verification/validation must be accomplished. Included in this verification/validation should be the insertion of the hardware faults identified in the hardware/software interface FMECA and/or Fault Tree.

What happens to reliability?

Reliability is defined as the probability of success or operation. The probability of inadvertent deployment is a subset of the probability of failure. The added circuitry required to decrease the probability of inadvertent deployment will decrease the reliability of the ECSU. However, due to the innovative design approach used on the CABS design, a major decrease in the probability of inadvertent deployment will be accomplished with only an estimated 5% decrease in Mean Time Between Failure (MTBF).

CONCLUSIONS

Based on the analysis of a complex occupant restraint system, (CABS), the FAA requirements appear reasonable and acceptable for specifying inadvertent deployment probability numerics. However, to meet these stringent FAA requirements, software and hardware designers must continue to investigate and employ innovative design solutions.

Description

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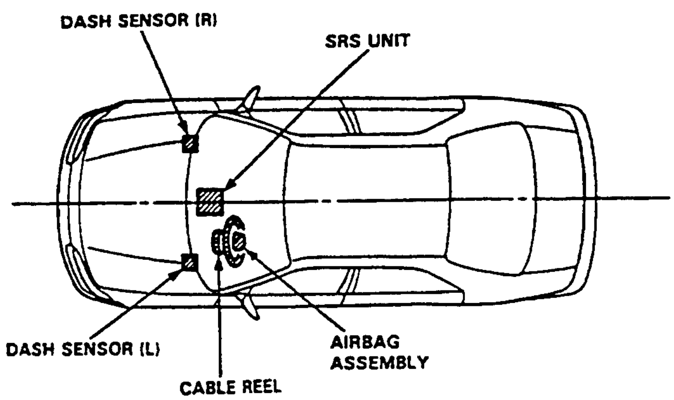
The SRS is a safety device which, when used in conjunction with the seat belt, is designed to protect the driver by operating only when the car receives a frontal impact exceeding a certain set limit.
The system is composed of left and right dash sensors, the SRS unit (includes cowl sensor), the cable reel and airbag assembly.

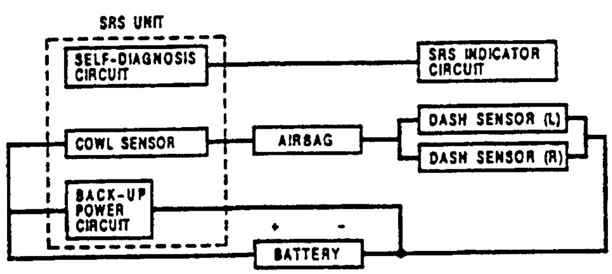


Operation
As shown in the diagram below, the left and right dash sensors are connected in parallel. This parallel set of sensors is connected in series with the airbag inflator circuit, the cowl sensor, and the car battery. In addition, a back-up power circuit is connected in parallel with the car battery. The back-up power circuit and the cowl sensor are located inside the SRS unit.

For the SRS to operate:

(1) The cowl sensor and one or both dash sensors must activate.
(2) Electrical energy is supplied to the airbag inflator by the battery, or the back-up power circuit if the battery voltage is too low.
(3) The airbag deploys.

The cowl and at least one dash sensor must be activated simultaneously for at least 0.015 seconds to deploy the airbag.



Self-diagnosis system
A self-diagnosis circuit is built into the SRS unit: when the ignition switch is turned ON, the SRS indicator light comes on and goes out after about 6 seconds if the system is operating normally. If the light does not light, or does not go out after 6 seconds, or if it comes on while driving, this indicates an abnormality in the system. It must be inspected and repaired as soon as possible.

Honda Civic, 1992 Service Manual **23-267**

Figure 1. Service Manual

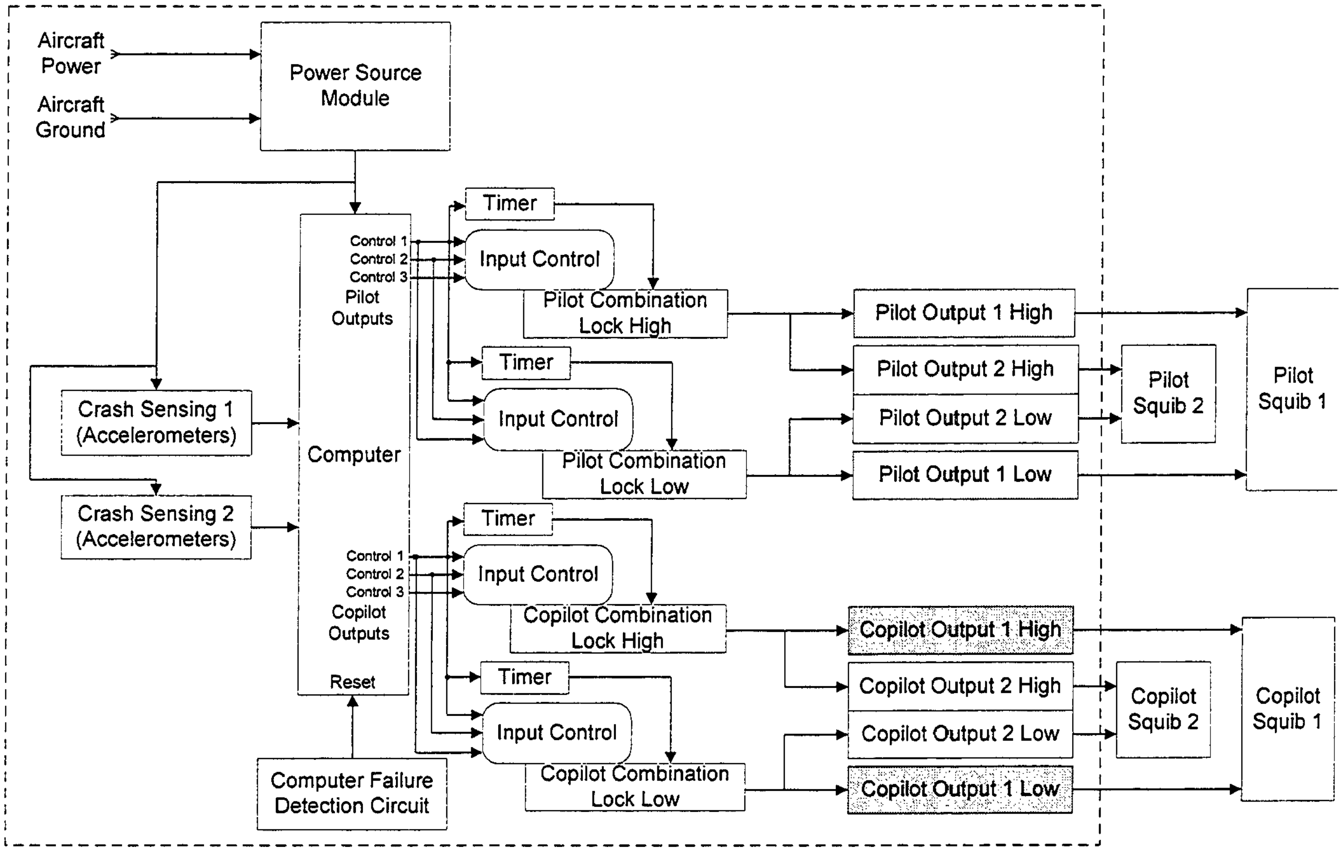


Figure 2. Electronic Crash Sensor Unit

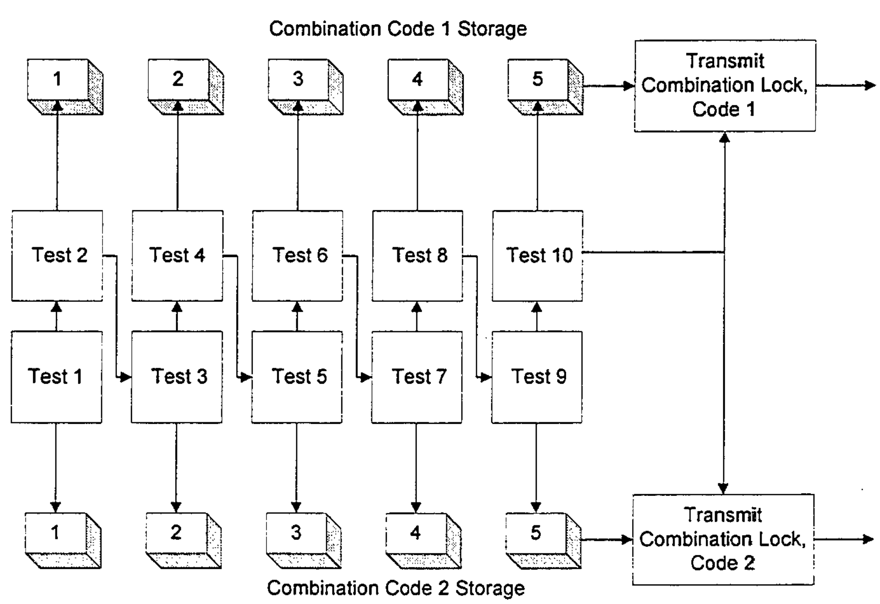


Figure 3. Block Diagram Software-Combination Lock

Effect of Airbag Deployment on Helicopter Flight Control

Frederick Brozoski
John Crowley
Philip Johnson
Joseph McEntire

U.S. Army Aeromedical Research Laboratory
Aircrew Protection Division
P.O. Box 620577
Fort Rucker, AL 36362-0577 USA

ABSTRACT

The ability of U.S. Army aviators to maintain flight control in the event of an inadvertent deployment of a cockpit airbag system (CABS) was investigated. Current and qualified UH-60 aviators were recruited to fly one-hour sorties in a modified NUH-60 research flight simulator. Simulated inadvertent CABS deployments were introduced into these sorties during six pre-determined flight maneuvers. The simulated deployments included uncommanded cyclic and collective motions, obstruction of the forward and lateral viewscreens, obstruction of the instrument panel, and an audible cue (used to crudely mimic airbag deployment noise). Data was collected on the severity of each simulated deployment as perceived by the test subjects, as well as on the probability of crashing and the time to recover from, or to crash as a result of, each simulated deployment. Results show the probability of crashing due to an inadvertent airbag deployment was greatest at high speeds and low altitudes, and crashes generally occurred more quickly than did recoveries.

ABBREVIATIONS AND SYMBOLS

AGL	Above ground level
CABS	Cockpit airbag system
ft	Feet
KIAS	Knots indicated airspeed
LSRDT	Left standard rate descending turn
MSL	Mean sea level
NOE	Nap of the earth
S&L	Straight and level
USAARL	United States Army Aeromedical Research Laboratory

INTRODUCTION

The crashworthy features of modern U.S. Army helicopters and aviator personal protective equipment have done much to reduce the potential for serious injury during survivable helicopter crashes.[1, 2] Even so, helicopter occupants still are at high risk of injury during survivable

mishaps; Shanahan and Shanahan have shown that approximately 80 percent of helicopter crash injuries are caused by impacts between the occupants and the aircraft structure.[1] To further reduce the incidence of these impact injuries, the U.S. Army has investigated the possibility of incorporating supplemental airbags in its helicopter fleet. These systems are expected to enhance the survivability of modern Army helicopters.[3, 4]

However, the use of any airbag system brings with it the risk of inadvertent deployments. Of interest in this study was the influence of inadvertent deployments on flight control. Several aspects of inadvertent deployments present a risk to flight control. First, high-speed video taken of live UH-60 prototype airbag deployments in an UH-60 aircraft have shown the forward and lateral airbags to move the flight controls (either through direct or indirect interaction with the cyclic and collective). Second, when fully inflated, the prototype airbags obstruct the aviator's view of the instruments, as well as out the aircraft's windows. Third, by definition, inadvertent deployments can happen at any time, including while occupants are out of the ideal body posture, thereby increasing the chance of causing physical injury to the aircrew. Any combination of these circumstances may prohibit the flight crew from maintaining effective control of the aircraft.

This study was undertaken to assess whether aviators could maintain aircraft control in the event of an inadvertent CABS deployment. While the possibility of aviator incapacitation due to airbag-induced injury is a threat to flight control, it was not addressed in the present study for human subject safety reasons. Rather, in this study, the effects of an inadvertent CABS deployment (i.e., uncommanded flight control motions and obstruction of the aviator's views of the instruments and outside the windows) were simulated in USAARL's NUH-60 research flight simulator. To evaluate the effects of these events on flight controllability, data was collected on several aspects of flight performance, including probability of crash, time to recover, and perceived difficulty.

RESEARCH METHODOLOGY

Test Subjects

Thirteen subjects were recruited for this study. Each subject was a qualified UH-60 aviator who was also current on the aircraft at the time of participation. All subjects possessed a valid Department of the Army Form 4186 ("up slip") stating that the aviator was fit for simulator flight.

Subjects selected for participation were briefed formally on their role in the study. They were advised that simulations of inadvertent airbag deployments would be introduced during a one-hour simulator flight, but they were not informed as to the nature of the simulated inadvertent deployment (e.g., loss of instruments or uncommanded flight control motions). The subjects were instructed that after each simulated deployment, they were to regain control of the aircraft and return as quickly as possible to pre-deployment parameters.

Simulator Sortie
Each subject flew a one-hour mission in USAARL's NUH-60 research flight simulator. The flight profile (Figure 1) was flown under visual meteorological conditions (VMC) with five miles visibility. The sorties were flown as single-pilot missions with the subjects seated in the right crewseat. During the flight, six simulated inadvertent CABS deployments (represented by X's in Figure 1) were introduced into the flight profile during specific maneuvers. The sequence of simulated deployments remained constant for all subjects.

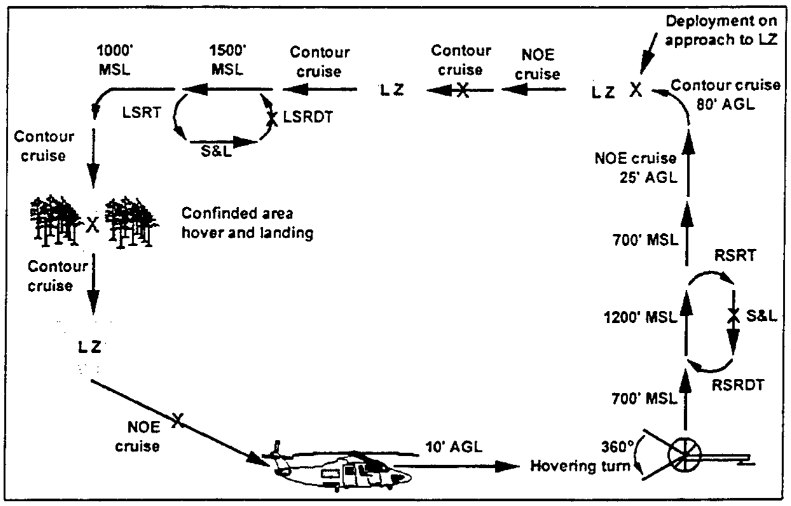


Figure 1. Mission flight profile. X's indicate the occurrence of simulated inadvertent deployments.

Simulated Inadvertent Deployments
The software that controls the simulator motion base was modified to allow the effects of inadvertent CABS deployments to be introduced at any time during the sortie. The parameters used to create the simulated inadvertent deployment were based on high-speed video of live prototype airbag deployments and airbag performance specifications. To simulate the results of airbag/flight control interaction, the software change allowed the investigator to specify representative flight control deflections, e.g. one-inch forward cyclic displacement. These deflections were reproduced in the motion base of the simulator and in the flight control itself. To simulate the temporary obstruction of the aviator's view outside the aircraft, the viewscreens (both forward and lateral) were turned white. Blacking out the instrument panel lighting simulated the temporary obstruction of the instrument panel. The software change also allowed the investigator to specify how long the viewscreens remained white and instrument panel lights were blacked out. An aural cue was also included to crudely mimic the sound associated with airbag deployment. The parameters used in simulating the inadvertent CABS deployments are presented in Table 1.

Table 1.
Parameters of simulated CABS inadvertent deployment.

Parameter	Event	Magnitude/duration
Cyclic motion	Forward Leftward	1 in. 1 in.
Collective motion	Downward	2 in.
Windscreen views	Displays turn white	3 sec.
Instrument view	Panel lights black out	5 sec.
Deployment noise	Aural cue	Approx. 1 sec.

Measurements and Analysis

During the simulator missions, flight performance data such as airspeed and radar altitude were collected. Also, each flight was recorded on videotape for later review. To gauge the flight safety implications, the subjects, simulator operator, and simulator observer were asked to rate the perceived severity of the event on a scale of 0% (no effect on flight safety) to 100% (certainty of a serious accident). The subjects were asked to rate the event immediately after regaining control of the aircraft (or crashing) and again, during a post-flight debriefing.

The likelihood, or probability, of crashing as a result of a simulated deployment was determined. The outcomes of each simulated inadvertent deployment, i.e. recovery or crash, were grouped according to the maneuver during which the event took place. For each maneuver, the percentage of simulated deployments that resulted in a crash was computed. The resulting percentage represented the likelihood of crashing if an inadvertent deployment was to occur during a specific maneuver.

Video records were used to determine time to recover from, or to crash as a result of, each simulated inadvertent deployment. Generally, this was taken as the time between the viewscreens turning white (the start of the simulated deployment) and either the subject arresting any erratic aircraft motions (resulting from the simulated deployment or their efforts to maintain control) or the aircraft impacting the terrain or an obstacle. For simulated deployments introduced during straight and level flight and left standard rate descending turns, time to recover was the duration of time between the initiation of the simulated deployment and the subject regaining his pre-deployment parameters, i.e. airspeed, altitude, heading, rate of climb, etc.

Simulator 'Timeout' Conditions

During some simulated inadvertent deployments, the modified flight simulator software used in this study caused the flight controls to malfunction (termed a "timeout" condition). Timeouts occurred when the flight controls were prohibited from maintaining their commanded positions (e.g., a two-inch collective drop). During timeouts, the simulator software 'fought' subjects for control; this was caused by the simulator software trying to return the flight controls to their commanded positions as the subject input corrective flight control motions. Timeout conditions

lasted the duration of simulated deployment (five seconds). Afterward, the subject regained full control of the flight controls.

Timeouts made recovery more difficult. Therefore, crashes with timeouts were excluded from the analysis. However, if a subject managed to recover the aircraft despite a timeout, the data were retained in the analysis. Fourteen simulated deployments were influenced by timeouts. In nine of the 14 cases, the subjects crashed, and the data were excluded from analysis.

RESULTS

Subject Population

A total of 13 subjects participated in this study. Data sets from 11 of the 13 were considered in the analysis. Two subjects data sets were unsuitable for analysis, because of one subject's prior knowledge of the experimental methodology and another's inability to maintain flight parameters. The 11 subjects had an average of 575 UH-60 Black Hawk flight hours and 1680 hours total flight time.

General

Figure 2 shows the indicated airspeed and radar altitude at the instant of deployment. Also shown is the probability of crashing associated with each maneuver. Straight and level flight and the left standard rate descending turn were performed at similar altitudes and airspeeds; therefore, a combined probability is presented.

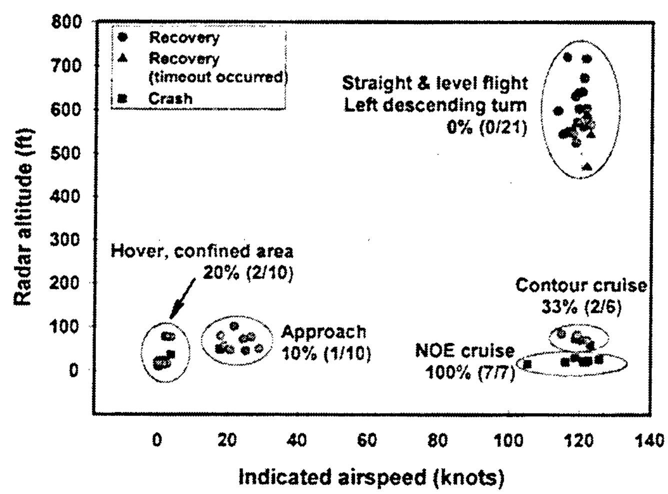


Figure 2. Probability of crash. Data shown include timeouts resulting in recovery.

Figure 3 shows the times to recover from, or to crash as a result of, the simulated inadvertent deployments. Note that subjects typically took longer to recover from a simulated deployment than to crash. This remained consistent for the approach and contour cruise maneuvers. With the exception of a single subject, the same trend is also evident during the confined area hover.

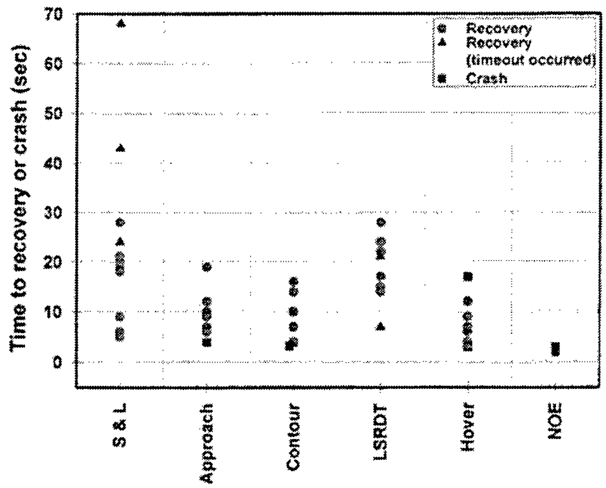
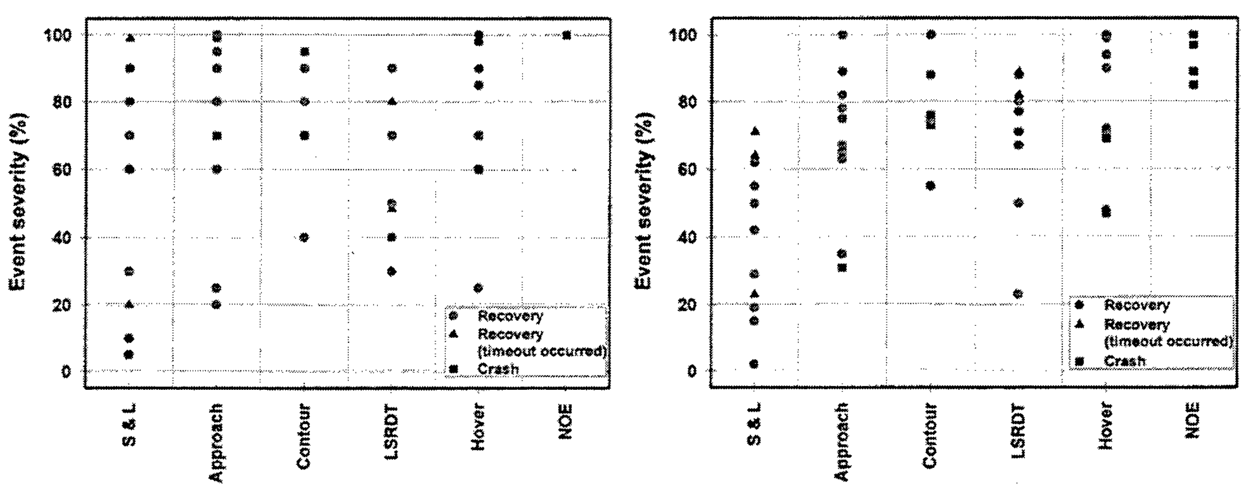


Figure 3. Time to recover (or to crash). Data shown include timeouts resulting in recovery.

Ratings of the severity of each simulated inadvertent deployment, as perceived by the subjects, were grouped by maneuver (Figure 4). Subject's responses varied greatly for all maneuvers except NOE cruise. In their initial verbal ratings, the seven subjects considered (four of the 11 subjects crashed as a result of timeout conditions) rated the severity of simulated deployments during NOE cruise flight at 100 percent (certainty of a serious accident). Post-flight ratings remained high, but three subjects lowered their respective ratings. Of these, the lowest rating was 85 percent.



(a) In-flight

(b) Post-flight

Figure 4. Event severity as perceived by test subjects. Data shown are subjects' (a) verbal response recorded immediately after regaining control of the aircraft or crashing and (b) written responses recorded during post-flight de-briefing. Data shown include timeouts resulting in recovery.

DISCUSSION

General

Crashing, as the result of inadvertent CABS deployment, appears to be least likely during maneuvers performed at high altitude (Figure 2). Almost every subject managed to recover from simulated deployments introduced during S&L flight and the LSRDT. One subject crashed resulting from a simulator timeout during the LSRDT. Each of these maneuvers was performed above 1000 ft MSL. The higher altitude allowed subjects to sacrifice altitude while regaining aircraft control. Also, the high altitude removed the potential for striking obstacles (e.g., trees, telephone poles, etc.) while the visual displays were obstructed.

The likelihood of crashing when at low altitude shows a possible dependence on forward airspeed (Figure 2). NOE cruise, contour cruise, hover, and approach maneuvers were all flown at or below 100 ft AGL. NOE cruise and contour cruise maneuvers were flown at 120 KIAS and were associated with the highest probabilities of crash of all maneuvers, 100 percent and 33 percent, respectively. Hover and approach were performed at similar altitudes but lower airspeeds, between 0 and 30 KIAS. The probabilities of crashing corresponding to approach and hover were lower, 10 percent and 20 percent, respectively. Further research would be required to determine more fully the nature of this relationship.

Crashes appear to be most likely within the first few seconds following an inadvertent deployment (Figure 3). Recovery times averaged 10.1, 10.2, and 6.4 seconds for the approach, contour cruise, and confined area hover maneuvers, respectively. With the one exception mentioned previously, aviators who crashed during these maneuvers did so within four seconds or less of the simulated deployments. Incorporating inadvertent deployments into aircrew training may provide a means of improving recovery time. A more refined simulation of inadvertent deployments would be necessary, as would the need to eliminate simulator timeouts.

Study Limitations

The simulated inadvertent deployments used in this study may have been too severe. The flight control motions were a worst case condition in which the effects of inadvertent deployments on both the right and left crewstations were inflicted on a single subject. The aviators' views out the windscreens may not be obstructed for a full three seconds, and the aircraft's forward and lateral windows may not be totally obstructed by the fully-inflated airbags. It is possible that some timeout conditions may have been caused by the fast reaction times of some subjects. These subjects may have reacted quickly enough to prohibit the flight controls from reaching or maintaining their commanded positions, thus introducing timeouts and possibly crashing as a result. For this reason, it is possible that some of the quickest subjects may have been excluded from the analysis.

However, in some ways, the simulated inadvertent deployments may have been too mild. First, the effects of possible airbag-induced injury to the aircrew were ignored. Second, the subjects knew that the simulated deployments were going to occur. Third, the magnitude of the control motions may have been underestimated; during a concurrent live airbag deployment study using anthropomorphic test devices, the airbags were observed to impart cyclic displacements of at

least twice those used in this study. Finally, few high power maneuvers (e.g., sling loads, mountain flying, etc.) were incorporated into the flight profile; maneuvers such as these would be more sensitive to the reduction in lift associated with the uncommanded collective displacement.

Future research should define better the specific characteristics of the real CABS, and minimize or eliminate the timeout problem. Other flight modes, such as high gross weight, sling load operations, or mountain flying should also be simulated.

CONCLUSIONS

This study explored the effect of inadvertent deployments of a prototype UH-60 CABS on flight control. To that end, simulated inadvertent deployments were introduced during several maneuvers typical to UH-60 Black Hawk missions. Based on the probability of crashing, time to recover, and perceived severity, three conclusions can be drawn. First, the potential for a crash due to a UH-60 prototype CABS inadvertent deployment was highest when the aircraft was flying at low altitude and high speed. Second, crashes were unlikely when inadvertent deployments occurred while the aircraft was at low speed or high altitudes. Third, the likelihood of crash was greatest within the first few seconds after an inadvertent deployment.

These effects may likely be attributed to the prototype lateral airbags. During simulated inadvertent deployments, subjects attempted to pull upward on the collective, thereby gaining altitude and reducing the risk of impacting the terrain or other obstacles while the viewscreens and instrument panel were obstructed. However, the interaction between the lateral airbags and the collective (represented by the two-inch drop in collective position) interfered with the subjects' attempts to increase altitude. A follow-on study is planned to assess the influence of the prototype UH-60 lateral airbags on flight control.

DISCLAIMER

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In-flight Inadvertent Deployment Test

Jin Woodhouse
US Army Aviation Applied Technology Directorate
Fort Eustis, VA 23604-5577

ABSTRACT

The UH-60A/L Cockpit Air Bag System (CABS) Engineering and Manufacturing Development (EMD) program for the development and qualification of the CABS for the UH-60 aircraft platform was initiated in September 1996 and is nearing its completion in December 1999. Under the EMD program, extensive design, development, and qualification testing have been accomplished to demonstrate that the CABS performs reliably and effectively to satisfy its primary mission functions. However, there are a few integration issues still remaining in the program, including redesign of the lateral bag module to eliminate or reduce the possibility of upper extremity injury and flight control interference, and incorporation of desired enhancements to the Electronic Crash Sensor Unit (ECSU). These remaining issues are planned to be addressed in the follow-on CABS Integration Phase. This paper represents the test report for the in-flight inadvertent deployment test that was conducted in October 1999 in support of the EMD program, which demonstrated that a pilot can maintain safe control of the aircraft during and after inadvertent or unnecessary deployment of the forward air bag. This was the first time that pilots were subjected to actual CABS deployment in the aircraft, both on the ground and in flight. This test also confirmed that injury risk and flight control interference are negligible when tested without the inputs/interference associated with the current lateral air bag configuration.

INTRODUCTION

BACKGROUND

The Aviation Applied Technology Directorate was the first to develop and implement the CABS as a supplemental aircrew restraint system for the Army helicopters. Following a series of Small Business Innovation Research (SBIR) contracts, a Phase III EMD contract, funded by the Project Manager, Aircrew Integrated Systems (PM ACIS), was awarded to Simula Safety Systems, Inc. in September 1996. Although the inadvertent or unnecessary deployment of CABS during normal flight is expected to be highly improbable, the CABS is designed to minimize adverse consequences should deployment in normal flight occur. Under the extensive EMD qualification test program which began in November 1998, the successful test results from the environmental test, dynamic drop tower/sled test, gas generator service release test, reliability test, bench-level and aircraft-level electromagnetic environmental effects (E^3) test have demonstrated that the CABS technology for helicopter application is proven and that CABS can operate reliably and effectively in the severe helicopter operating environment. In addition, in support of the EMD program, numerous on-aircraft deployments were conducted with anthropomorphic

test dummies (ATD) to evaluate potential flight control interference and injury risk which could adversely impact the pilot's ability to maintain safe control of the aircraft during and after an inadvertent or unnecessary deployment of the CABS. In May 1999, when an instrumented arm for the ATD became available for the first time for the program, the US Army Aeromedical Research Laboratory (USAARL) was able to obtain arm injury data in support of the UH-60A/L CABS Inadvertent Deployment Evaluation. Based on the data collected, USAARL determined that flight control interference and upper extremity injuries were likely to occur as a result of the lateral air bag deployment in both crash and normal flight conditions (ref 1). In addition, during the USAARL Flight Control Effects Study in a UH-60 simulator, which was also part of the UH-60A/L CABS Inadvertent Deployment Evaluation, it was observed that a primary contributor to the mishap/crash event was the cyclic/collective flight control interference from the interaction of the deploying lateral air bag with the pilot or co-pilot's outboard arm. Based on these results it was evident that the lateral air bag module redesign was necessary to complete the CABS integration effort for the UH-60A/L CABS. Under the current Army CABS revised Acquisition Strategy, the remaining integration issues including the lateral air bag module redesign and the repackaging of the desired enhancements for the ECSU will be completed in the follow-on CABS Integration Phase upon approval of the Milestone III Decision Review MDR III, Part 1 in December 1999. In support of the MDR III, Part 1, AATD was tasked by PM ACIS conduct the in-flight inadvertent deployment test with forward air bag modules only to demonstrate that inadvertent or unnecessary deployment of the forward air bag modules will not result in a loss of control of the aircraft and that the injury risk and flight control interference issues would be eliminated or are within the acceptable limits, when tested without the inputs/interference associated with the current lateral air bag module configuration.

TEST OBJECTIVES

The primary objective of the test was to evaluate the effects of an inadvertent or unnecessary deployment of a forward air bag upon a pilot's ability to maintain safe control of the aircraft. The secondary objectives were to evaluate in-flight emergency procedures to use following an inadvertent or unnecessary deployment of the forward air bag module and to evaluate the cockpit compatibility of the installed forward air bag modules.

TEST SCOPE

The supporting documentation for airworthiness release for this test was reviewed by an AATD Safety of Flight Review Board (SOFRB), independent from the AATD CABS team. Based upon a positive recommendation from the SOFRB, the Commander, AATD, granted a flight release for the purposes of this test under his delegated authority from the Commanding General, U.S. Army Aviation and Missile Command.

Since the lateral air bag module is planned for redesign in the follow-on CABS Integration Phase due to the potential injury risk and flight control interference identified during the previous USAARL testing, the test was conducted with forward air bag

modules only. In addition, due to the limited number of qualification test hardware available under the UH-60A/L EMD program, a total of six deployments of the forward air bag modules were conducted with three air bags being deployed from each cockpit crew station. Furthermore, for safety considerations, the test was conducted in two phases, the ground deployment phase and the in-flight deployment phase and only one forward air bag module at a time was deployed in each crew station of the pilot in control of the aircraft for each test. During the ground test, each pilot was subjected to one dry-run deployment in his crew station to confirm that there would be no safety concerns for the follow-on in-flight deployments and to evaluate emergency procedures for the in-flight deployment phase, if necessary. In order to synchronize external high-speed video with onboard instrumentation, the safety pilot announced the deployment and the test pilot was also aware of the countdown and air bag deployment during the ground test only. To simulate inadvertent or unnecessary deployment in flight, the non-flying pilot was designated as the safety pilot for each test and deployed the air bag manually using the air bag firing trigger system on the lower console, with no warning given to the flying pilot. The non-flying safety pilot was responsible for taking control of the aircraft if he determined that the flying pilot was approaching the aircraft maneuvering limits specified in the UH-60A/L Operator's Manual (ref 2). It is noted that the highest level of concern for safety was maintained throughout the conduct of this test program. The safety pilot always verified the safety of the overall situation and activated the two firing switches of the air bag firing device only when the flying pilot was in an normal upright flying posture and that his arm would not be in the air bag deployment path. The helmet visors were also kept down during each test. The crew chief was also prepared to operate the onboard fire extinguisher after each deployment, if necessary. In addition, since it was noted in other previous test that the covers became detached upon deployment, which could become a hazard in the aircraft, the modules for the in-flight deployments were replaced with improved modules that had non-detachable covers (the intended production configuration). There were no other differences between these modules. The modules with non-detachable covers were not available for the ground test and regular strapping tape was applied at the hinge to temporarily fix the cover detachment problem. To prevent injury from accidental firing during installation, the electronic caps/ and/or grounding pins were not removed until just prior to each test (ref 3).

TEST METHODOLOGY

A qualitative electromagnetic compatibility safety-of-flight test was completed by ATTC prior to the initiation of the CABS in-flight inadvertent deployment. Pretest checks of the aircraft and proper installation of the forward air bag modules and the instrumentation package were completed by the AATD aircrew/test director and the ATTC instrumentation personnel.

The tests were conducted in accordance with the AATD test plan (Appendix A), the AATD safety of flight airworthiness release (Appendix B), and the UH-60A/L Operator's Manual (ref 2) except for the seat position for the flying pilot. During the ground test, the rotors remained static and a portable ground power unit provided an external electrical power to operate the aircraft hydraulic system permitting movement of flight

controls during the ground test. In-flight deployments were conducted under the following conditions: one deployment in each crew station in straight-and-level forward flight at 90 knots indicated air speed (KIAS) and approximately 1500 feet above ground altitude (AGL) and also one deployment in each crew station in an out-of-ground effect (OGE) hover at approximately 100 feet AGL. The pilots' assessment of the inadvertent deployment event was the primary evaluation factor in this test. The quantitative aircraft controllability evaluation criteria shown in Table 1 was established based on the TC 1-212 Aircrew Training Manual for UH-60.

Table 1 - Aircraft Controllability Evaluation Criteria

		Forward Flight	*Hover (OGE)*
Pitch Change	Desired	±5°	±5°
	Adequate	±10°	±10°
Roll Change	Desired	±5°	±5°
	Adequate	±10°	±10°
Altitude	Desired	±100ft	±5ft
	Adequate	±200ft	±10ft
Airspeed	Desired	±10 KIAS	–
	Adequate	±15 KIAS	–
Heading	Desired	±10°	±10°
	Adequate	±20°	±20°
Trim	Desired	±½ ball	–
	Adequate	±1 ball	–
Drift	Desired	–	±5ft
	Adequate	–	±10ft

Forward Flight: Speed=90±10 KIAS; Altitude ≥1000 ft AGL; control forces trimmed; straight and level
Hover: Altitude ≥100 ft AGL; control forces trimmed
Values based on TC 1-212 Aircrew Training Manual for UH-60
Take readings ~3-5 sec after CABS deployment

DESCRIPTION

Aircraft

A standard Army UH-60A Black Hawk (Army Serial Number 84-23983) from the US Army Aviation Technical Test Center (ATTC), that was instrumented for the UH-60A/L CABS limited Developmental Test (DT), was signed over to AATD and the in-flight inadvertent deployment tests were conducted by two AATD test pilots and an AATD crew chief on 18-20 October 1999 at the US Army Cairns Army Airfield, Ft. Rucker, Alabama.

UH-60A/L CABS

The CABS is a supplemental restraint system designed to provide a significant reduction in the head and upper torso flail to prevent serious and fatal injuries during severe, but survivable aircraft crashes. The UH-60A/L CABS consists of an A-kit and a B-kit. The A-kit consists of three interconnection wiring harnesses, circuit breaker, two aluminum glareshield stiffening brackets, two composite reinforcement doublers fastened to the glareshield and one aluminum support bracket for the Electronic Crash Sensor Unit (ECSU). The B-kit consists of one forward air bag module and one lateral air bag module for each aviator crew station, and one omni-directional and programmable ECSU. The forward air bag modules are installed in the glareshield forward of each of the pilot seats and the lateral air bag modules are mounted on the stationary portions of the side armor panels outboard of each aviator. The ECSU is installed in the seatwell below the copilot seat on a support bracket with its electrical connectors facing the forward direction. The support bracket is attached to the inboard side of BL 35 and to the top flange of BL 30 with the forward edge of the support bracket located at approximately STA 235 (ref 4).

For the purpose of this test, the lateral air bag modules were not installed and the ECSU, which was installed for the planned DT, was disconnected from the air bag firing circuit.

TEST EQUIPMENT

Forward Air Bag Modules

The forward air bag module shown in Figure 1, consists of an aluminum housing with mounting flanges for glareshield attachment, a pyrotechnic gas generator, an asymmetric 60-liter air bag constructed of neoprene-coated nylon material, and a plastic cover. The cover is hinged at the gas generator side of the module to allow the pressurized air bag to force the cover open down towards the instrument panel without losing retention of the cover. The forward modules are mounted about four inches inboard of center on each crewmember and canted 20 degrees to the outboard toward the crewmember as shown in Figure 2. The location is the result of an extensive Simula/Sikorsky integration effort to identify the best location for module performance while minimizing the impact on the field of view and relocation of onboard aircraft subsystems. It is noted that the mounting bolts for the forward modules were installed from the bottom up deviating from the current CABS installation instructions and the General Aviation Maintenance Manual to preclude potential air bag rupture noted during the previous CABS testing.

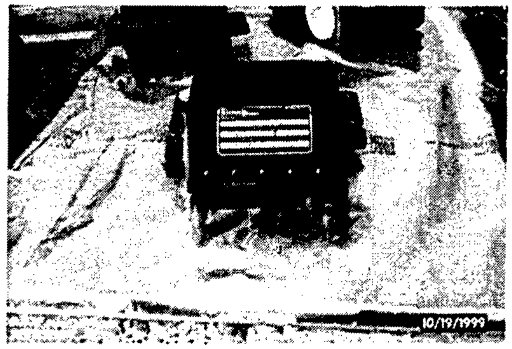

Figure 1 – UH-60A/L CABS Forward Air Bag Module

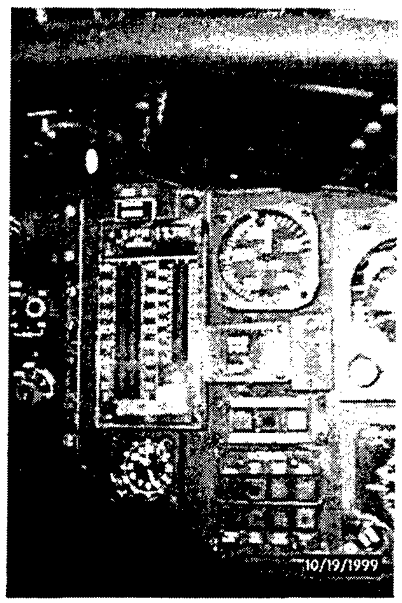

Figure 2 – Installation of Forward Air Bag Module in UH-60A

Reinforced Glareshield

The maximum air bag deployment reaction load imparted on the glareshield by the forward air bag module is about 1300 lb. To restrain the motion of the glareshield during the forward air bag deployment, the UH-60A glareshield is modified with composite reinforcement doublers and aluminum glareshield stiffening brackets as part of the A-kit. A modified glareshield, provided by Simula to accept the forward air bag modules, was already installed on the test aircraft for the planned DT.

Air Bag Firing Device

The manual air bag firing device was placed on the lower console panel as shown in Figure 3. For safety considerations, to deploy the system, two switches had to be activated for each deployment, one toggle switch to arm and one of the other two momentary switches to fire the air bag in the test crew station. This set up was to preclude accidental firing before and during the test and provide for a double check for

the safety pilot that the pilot to be subjected to deployment was in proper upright position without his arm reaching for the instrument panel prior to deployment.

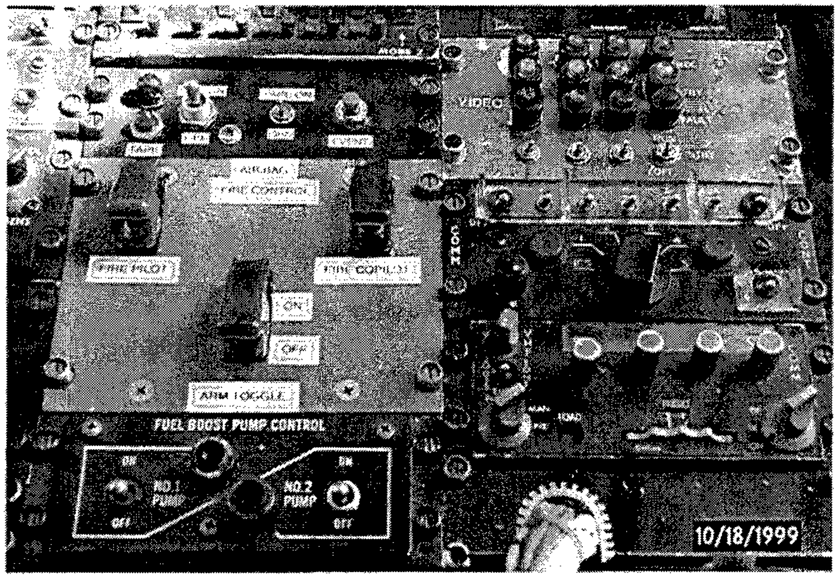

Figure 3 – Manual Air Bag Firing Device and Event Switch

Test Subjects

The pilots' anthropometry was measured by the ATTC Human Factor Evaluation specialist and is documented at Appendix C.

Both pilots were dressed in standard issue aircrew clothing, comprised of flight suit, survival vest, Nomex gloves, flight helmet, and boots. Night vision goggles were not required. The standard survival knife was not available until Test 6 and a regular pocketknife was used during the evaluation of emergency procedures.

Seat Positions

The pilot and the copilot seats incorporate pins that slide into holes on the horizontal and vertical rails to maintain seat position. The seat positions for each test were noted by the number of holes visible from the front on the horizontal rail and from the top of the vertical rail as shown in Table 2. During the initial *ground test*, in accordance with the AATD test plan, the pilots attempted to adjust the seats to approximate design-eye-height. However, only the pilot (69 percentile in height) was able to sit at the design-eye-height and be able to fly although that position was much further forward than his normal flying position. The co-pilot (98 percentile in height) could not fly if he was to sit at the vertical design-eye- height. Therefore, during the *ground test*, the co-pilot positioned the seat so that he was able to fly while being as close to the design-eye height as possible. In the interests of safety during the *in-flight* deployments, an authorization was obtained from the AATD SOFRB Chairperson to deviate from the test plan and allow both pilots to conduct the deployment tests in their normal flying positions.

Table 2 - Pilot/Co-pilot Seat Positions

Test	Visible horizontal holes	Visible vertical holes
Ground Test # 1 (pilot)	2	6
Ground Test # 2 (co-pilot)	6	3
Test # 3 in Forward Flight (pilot)	6	8
Test # 4 in Forward Flight (co-pilot)	6	2
Test # 5 in Hover (pilot)	6	8
Test # 6 in Hover (co-pilot)	6	2

Instrumentation

Due to the time and cost constraints, the instrumentation was limited to the instrumentation package that was built by ATTC for the planned CABS DT and only a limited set of aircraft performance data was collected in addition to the inboard video coverage in flight. The data includes airspeed, pressure altitude, altitude rates of ascent and descent, attitude (yaw, roll, and pitch) rate, accelerations at the aircraft CG and near the ECSU mounting location, and event/firing count. The instrumentation consisted of two sub-packages; the Pulse Code Modulator (PCM) data package and the video package and was mounted on an instrumentation pallet as shown in Figure 4. The PCM data package consists of: 1) Two tri-axial accelerometers, one located next to the ECSU mounting location and the other placed at the aircraft CG location (as noted earlier, the ECSU was installed for the planned DT and was not connected to the firing circuit for this test), 2) Rate Gyro located on the instrumentation pallet close to aircraft CG location, 3) Air data transducer located at the nose of the aircraft, 4) PCM data event switch located on the lower control panel as shown in Figure 3, and 5) Air bag firing device also located on the lower console panel. All data were collected through the Metraplex Data Acquisition System. The data was then processed into the PCM data stream and encoded to the video signal via the Merlin Encoder. The data output from the Encoder will be routed to the TEAC Recorder along with the time input from the Time Code Generator to be recorded on the 8mm tape. The video package was set up with two regular speed video cameras installed on vertical rails, one behind each crewmember pointing the cyclic control and the crewmember in the opposite crew station. Video output from the camera Controllers was provided to the Video Time Inserters where time from the Time Code Generator is merged into the data. The combined data was recorded by the video recorders on VHF tapes.

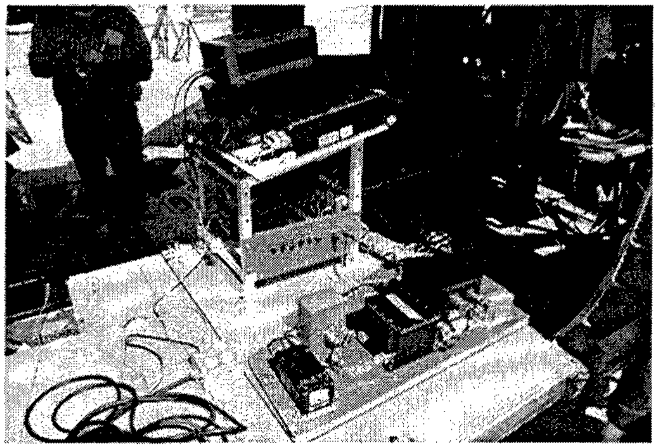

Figure 4 – Instrumentation Pallet

All communications either over the intercom or through the radios were recorded for use during the data reduction phase of the test. The cockpit voice was tapped through the safety pilot's head set and connected to audio channel of the video recorders. The test pilot's ICS switch for communication between the pilots was turned off during the deployment in flight so that the test pilot could not hear the safety pilot's count down prior to initiating the air bag firing trigger.

Video/Photo Coverage

Two onboard video cameras recorded the air bag deployment and the pilot/safety pilot reactions for each test. In addition, to record and note any discernable movement in the test aircraft, air-to-air video coverage of the test aircraft from a ATTC chase aircraft during deployments in straight-and-level forward flight and ground-to-air video coverage during deployments in hover were provided by the ATTC photographer. During the ground test, both forward aircraft doors were removed and additional high-speed video (250 frames per second and 500 frames per second) and high-speed film (1000 frames per second) cameras provided by ATTC and AATD were set up laterally by the pilot and co-pilot's doors. In addition, digital photographs of pre- and post-test cockpit were taken as necessary.

RESULTS AND DISCUSSION

Pre-flight Briefing

Prior to the ground deployments and in-flight deployments for each flight condition, the pre-flight briefing was conducted by the pilot and the test director and was attended by all crewmembers. The pre-flight briefing included the review of the mission-briefing checklist, safety aspects of the test, individual test responsibilities, and crew coordination.

Conduct of Test

All tests were considered to be successful based on the results that at no time during any of the tests, did the pilot lose control or come close to losing control of the aircraft during and after the inadvertent deployment. The video/high speed film analysis and cursory analysis of the instrumentation data also confirmed that there were no discernable movement in the aircraft during and post each inadvertent deployment. The air bag deployment happened so quickly that both pilots commented that the event was "over" before they realized what had happened. Both pilots also noted that the noise (described as a muffled balloon pop) and startling effects of the inadvertent deployment were minimal and did not affect the pilots' ability to maintain safe control of the aircraft. In all tests, the forward air bag did not strike the cyclic upon deployment. The air bag began to partially deflate due to the change in air bag gas temperature within approximately one second after the deployment. Once the bag began to deflate, the pilots found it easy to move the bag around to view the instruments. When the partially deflated air bag drooped down and rested on top of the pilot's leg and on the cyclic, it did not restrict the cyclic control movement in forward flight, hovering flight, or during ground taxi. Approximately ½ inch movement forward and back to the original position was noted in the high speed film, which was due to the pilot arm movement after the bag hit the pilot on the chest. The strike on the chest was not strong enough to cause any bruise. The smell of smoke/fumes from the burnt gas generator propellant was noticeable, but the pilots did not report a loss of visibility or respiratory ailment except for the temporary coughing. The co-pilot also sensed radiant heat on his legs from the air bag deployment, but it did not cause any discomfort. During the second in-flight deployment, the co-pilot was struck on the right forearm upon deployment, leaving a minor abrasion with redness and swelling over an area of about 2.5 in x 1.5 in. However, this did not preclude the co-pilot from safely maintaining the control of the aircraft nor did it cause any significant movement in the aircraft. The abrasion was hardly noticeable after 2-3 days.

Since the CABS is a non-vented bag, the air bag never completely deflated and, while the partially deflated bag could be easily moved for momentary viewing of the instrument panel, it became a nuisance in continued flight, as it blocked a portion of the flight instruments and caution panel. The partially deflated bag would not stay stowed on top of the glareshield. Therefore, both pilots agreed that the air bag could be completely deflated by simply inserting a knife into it from top down (this was determined through experimentation to be easier than inserting it from bottom up) and squeezing out the gas and fumes. The pilots also observed that by holding the cut of the bag towards the cockpit window while squeezing the bag, the smoke/fumes could be easily vented overboard with minimal nuisance to the pilot. Once deflated, the bag could be easily rolled up and stowed on top of the glareshield. This allowed the pilots to see all the primary flight instruments and had only a minimal impact on the external FOV. If further flight is required, the air bag could be easily cut away in less than one minute during flight. The module cover continued to obstruct the airspeed indicator, top one third of the pilot display unit (PDU), the digital torque readout, and portion of the "chicklets" on the PDU on the pilot side and the radar altimeter and a portion of the "chiclets" on the PDU on the co-pilot side. Therefore, if further flight is required, both the air bag and the

module cover could be cut away, which took about 80 seconds to execute with the standard survival knife. During the ground test, it was discovered the air bag cover striking the PDU upon deployment damaged the PDU faceplate. Subsequent in-flight tests were conducted with a clear cover made of Flexene material over the PDU. The CABS is designed as a one-time use system and therefore, when the tests were repeated using one glareshield, glareshield damage was noted in several locations after the second deployment. This may have contributed to the seemingly inconsistent deployment trajectory striking the pilot when the pilot was seated further aft.

Installation of the forward air bag module presented minimal or no change in the pilots' field-of-view (FOV), did not obstruct any of the flight instruments, and did not interfere with any normal cockpit procedures for the UH-60 aircraft. The detail discussions of the test result are reported in the pilots' daily flight report and the test summary, which are provided as Appendix D.

The instrumentation data was reduced by ATTC and is provided as Appendix E.

Post-Test Briefing

After the ground test and each flight, a post -test briefing was conducted by the pilots to provide their assessment of the inadvertent deployment event on aircraft controllability.

CONCLUSIONS

- It has been demonstrated that an inadvertent or unnecessary deployment of the forward air bag in flight, however unlikely, will not preclude the pilot's or copilot's full use of cyclic flight control and will not cause a loss of control of the aircraft during or after the deployment.

- It has also been demonstrated that the inadvertent deployment or unnecessary deployment of the forward air bag during normal flight will not cause any significant injury or discomfort under the conditions tested to hinder the pilot's ability to maintain safe control of the aircraft. Therefore, the forward air bag deployment during crash conditions should not cause any significant injury to prevent the crewmember from exiting the aircraft after the crash.

- It was confirmed that the injury risk and flight control interference are negligible when tested without the inputs/interference associated with the current lateral air bag configuration.

- Following the inadvertent deployment continued safe flight under VFR or NOE conditions can be easily accomplished without further deflating the bag with a knife. However, continued flight under IFR will require, at a minimum, the forward air bag to be deflated.

- The noise and startling effects of the inadvertent deployment were minimal and did not at any time affect the pilot's ability to maintain safe control of the aircraft.

- The fumes resulting from burnt gas generator propellant upon air bag deployment and after the air bag was cut as an in-flight emergency procedure were annoying and unpleasant, but did not appear to hinder the pilot's ability to maintain safe control of the aircraft or result in respiratory ailment.

- Installation of the forward air bag module did not affect the pilot's FOV, obstruct any of the flight instruments, nor interfere with any normal cockpit procedures for the UH-60.

RECOMMENDATIONS

- The UH-60A/L CABS program should continue into the follow-on CABS Integration Phase to complete development and performance verification testing of the lateral air bag module redesign.

- If future lateral air bag module deployment testing with anthropomorphic test dummies in the UH-60A/L aircraft is successful without any injury or flight control interference, consider eliminating the in-flight inadvertent deployment testing to qualify the system.

- At a minimum for in-flight emergency procedure, the forward air bag should be deflated if continued flight is necessary. If continued flight under instrument meteorological conditions (IMC) is necessary, the flight crew should consider cutting away both the deployed forward air bag and the cover. Additional testing/simulation should be considered to evaluate simultaneous inadvertent deployment of both forward air bags under IMC.

- Add "Caution/Warning" to the CABS Operation and Maintenance manual and the Training manual describing which instruments may be unusable after an inadvertent or unnecessary deployment, either by obstruction by the deployed bag or instrument damage due to the strike impact of the cover upon deployment. Also, add the in-flight emergency procedures to be executed, should an inadvertent or unnecessary deployment occur in VFR or IFR flight.

- Redesign of the forward air bag module cover to eliminate damage to the PDU upon forward air bag deployment is not recommended as the PDU damage is not of a great concern during an actual crash.

- The PDUs should be protected with durable clear covers during any future performance verification or production-prove-out testing to avoid any unnecessary replacement cost.

- Conduct an analysis to determine if the variability in air bag trajectory noted during the test is due to the damage to the glareshield or the use of Simula-fabricated glareshield in lieu of an actual glareshield.

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APPENDIXES

A. AATD Test Plan
B. AATD Safety of Flight Airworthiness Release
C. Pilots' Anthropometry Data
D. Pilots' Daily Flight Reports and Flight Test Summary
E. Instrumentation Data

BIOGRAPHY

Ms. Jin Woodhouse is the project engineer for the UH-60A/L CABS program, at AATD, Fort Eustis, Virginia. She also has over twelve years of experience in aircraft/aircrew survivability technologies as an aerospace engineer. She holds B.S. and M.E. degrees in Engineering from the University of Virginia.

Design Considerations for Aircraft Crash Sensing

Robert F. Gansman
Simula Safety Systems, Inc.
Applied Technologies Division
7414 S. Harl Ave.
Tempe, AZ 85283
gansmanb@sssi.simula.com

ABSTRACT

Crash safety systems are being developed and introduced into commercial and military aircraft at an increasing rate. Effective crash sensing systems are needed to activate these safety devices. The operating environment of an aircraft imposes unique design requirements. For aircraft crash sensors to work reliably and effectively, their designers must consider complex crash kinematics, motion caused by extreme maneuvers and weapons fire, temperature extremes, and severe electromagnetic fields. Both hardware and crash discrimination software must work effectively throughout the entire range of conditions. A full characterization and understanding of these environments, and the requirements they impose, is critical to fielding a successful design.

INTRODUCTION

Innovations introduced over the past 30 years, such as energy absorbing seats, improved restraints, and crashworthy fuel tanks, have significantly reduced injuries caused by excessive spinal loads, crushing, impaling, and post-crash fires in aircraft crashes. Because of these innovations, the severity of crashes that can be survived has increased to the point that existing restraint systems are no longer adequate. Now, most serious injuries during a survivable crash are related to excessive flailing of the occupants that allows them to strike interior objects (Zimmerman, et al., 1989). Supplemental inflatable restraints are being introduced that, when working with the existing restraints, will effectively control occupant flail and continue to extend the limit of survival in severe crashes (Smith and Desjardins, 1998). Inflatable restraints are the next step in the evolution of occupant crash protection systems for aircraft.

All active crash safety systems, like inflatable restraints, need some means to determine that a crash is occurring. Crash sensors developed for automobiles are accurate and reliable because the designers fully understand the normal operating and crash environments. But the helicopter operating environment is much different from that of a car. Major differences include severe climatic changes, complex crash kinematics, severe vibrations, and the need to operate in strong electromagnetic fields. Further, the ability to conduct aircraft crash testing is severely limited by cost. These differences create a unique set of aircraft-specific requirements that drive the hardware and software designs (Zimmerman and Rogers, 1995). Recent work on cockpit air bag systems (CABS) has led to a much better understanding of the crash sensing considerations, both hardware and software, for aircraft applications.

SOFTWARE CONSIDERATIONS

Crash Algorithm Development

Crash discrimination is the main software consideration. Crash discrimination algorithms process sensor output to decide whether a crash is occurring. The automotive industry has reduced the design of crash sensing systems to a routine for cars. The process consists of selecting sensors and their mounting locations, then conducting road tests and crash tests with those locations instrumented. The road tests provide data to ensure that the sensors and algorithms will not cause air bag deployment during normal use conditions such as traveling around curves, over speed bumps, potholes, rough roads, and during emergency braking. The crash tests ensure that the algorithm will allow air bag deployment in serious impacts in time to protect the vehicle occupants, and that the air bags will not deploy in minor crashes, where they are not needed. Crash testing may include low and high speed barrier crashes, offset and angled crashes, lateral cashes, and pole and curb impacts. Tests may be repeated to gather a statistically significant sample.

Given this wealth of data, automotive industry researchers have been able to investigate many sophisticated algorithms. While the details are often proprietary, the basic approaches for different methods have been published. These include neural networks, frequency domain analysis, and different combinations of acceleration-derived quantities, such as position, velocity, acceleration squared, jerk (acceleration rate), energy (velocity squared), power (energy rate), and power rate. From the excellent injury reduction performance and safety record of automotive air bag systems, we can infer that many different discrimination schemes have been successfully implemented.

Developing discrimination algorithms for helicopters is more difficult. A flying vehicle can sustain significant crash forces in all directions, whereas a ground vehicle's operation is primarily two-dimensional (forward and lateral). A flying vehicle can crash on loose or hard soil, through vegetation, or in water, each of which has a very different dynamic response. The need to define a larger range of crash conditions requires more tests to be completed. But helicopters are expensive, and crash testing them is not practical. The military usually conducts a handful of crash tests each year, but on a variety of airframes and typically without sensors installed at potential crash sensing locations. Qualitative data is available from accident records, but post-crash investigations provide only crude estimates of the peak accelerations and total velocity change—far short of the detail needed.

The limited amount of helicopter crash data virtually prohibits the use of complicated algorithms that must be trained, tuned, or calibrated with real data. For example, a frequency-based algorithm would require data defining the frequency content of most types of crashes. Otherwise, it may fail to recognize a crash or activate the restraints too late to protect the occupants. Algorithm optimization must also be started anew for each different airframe, because each will have a different frequency response.

Given the lack of crash data, an effective helicopter crash discrimination algorithm must be based on the fundamental physics of vehicle kinematics. For example, we know without having any data that non-crash events like maneuvers have low accelerations with high velocity changes, and shocks, such as weapons discharge, have high accelerations with low velocity changes. Only crashes cause both high accelerations and high velocity changes. We also know that a more severe crash will have a higher velocity change, and thus a velocity change threshold based algorithm can be made to fire sooner in a more severe crash – the desired trend. Such a physically based algorithm will always behave in a predictable manner, and can be extrapolated with confidence beyond the range of conditions tested. Predictable extrapolation allows the use of simple safety factors when setting deployment thresholds based on non-crash sensor data. This kind of physical intuition is absent with regard to quantities like frequency response.

The other aspect of algorithm development, tailoring an algorithm to not deploy during normal vehicle use, is no more difficult on helicopters than for ground vehicles. It simply requires that flight and ground tests be conducted to gather sensor data in all possible aircraft operating modes. These might include taxi, takeoff, landing, extreme flight maneuvers, weather induced turbulence, external stores jettison, cargo jettison, weapons discharge, and hard landings where the air bags are not needed. The CABS programs have led to a better understanding of both the normal and crash dynamics that discrimination software must consider.

Normal Aircraft Dynamics

The UH-60A/L and OH-58D CABS programs both included extensive testing to define the normal aircraft dynamics at potential sensor mounting locations. Military flight test engineers and test pilots at the U.S. Army Aviation Technical Test Center (ATTC) in Fort Rucker, Alabama, planned and completed tests that included all conceivable operating modes that might produce non-trivial accelerations. Both helicopter types were flown in extreme maneuvers up to the limits specified in their operating manuals. Many takeoffs and landings were completed at the maximum allowable climb and descent rates. All aircraft mounted weapons, including machine guns, rockets, and missiles, were discharged both singly and in combination. An 8000 pound load of cement filled barrels, attached to the cargo hook of a UH-60A, was dropped by pyrotechnically cutting the cable, suddenly reducing the combined cargo and aircraft weight by over a third and inducing a rapid ascent. A heavy wrench was dropped and a tool hammered near the sensors.

The data could be reduced and presented in any number of formats to characterize the dynamic operating environment of these two helicopters. The data presented here are acceleration and velocity change (the integration of acceleration) because the CABS algorithm is based on these fundamental physical quantities (Gansman and Derouen, 1998). The acceleration has been band-pass filtered to include only those frequency components between about 0.1 and 300 Hz, the primary frequency range during the crushing of aircraft structure. The acceleration is integrated with a windowing approach. The window can be set to any value and is one of the parameters adjusted for optimum

algorithm performance. All data presented here has been integrated with a 100 msec window for uniform comparisons, and because the major structural crushing in a crash is often complete within that time frame.

Figure 1 shows the peak resultant acceleration and velocity change in a series of flight tests for both helicopter types. The resultant acceleration indicates the maximum value, but in no specific direction. The OH-58D data are to the left of each chart and the UH-60A/L data are to the right. For the OH-58D, the highest accelerations occur during missile launch and machine gun fire. Machine gun fire on the UH-60A/L produces much lower accelerations. This is because the UH-60A/L is about three times heavier than the OH-58D, and the same forces from the machine gun will move the heavier aircraft less. Despite high accelerations, all of the weapons discharge events produce small velocity changes, indicating little energy input and small overall motion of the vehicle.

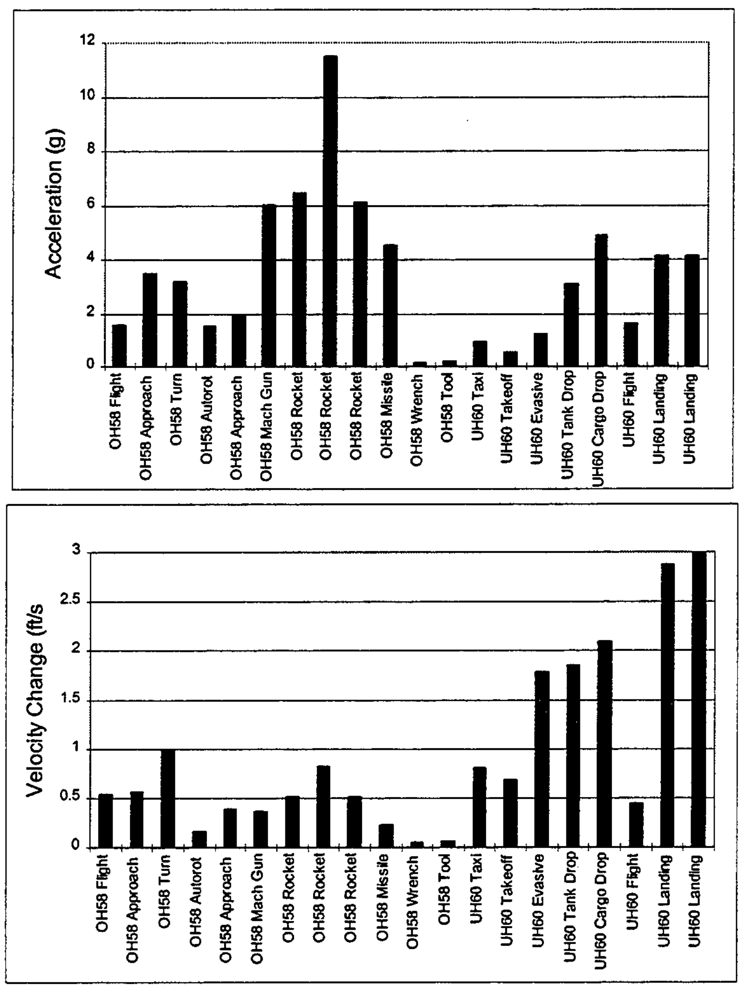

Figure 1 – Peak acceleration and velocity change in a series of flight tests

The highest velocity changes occur during a slow turn of the OH-58D, and during cargo jettison and landing for the UH-60A/L. The UH-60A/L is a heavy utility helicopter; its mission includes carrying heavy loads, and it can land hard on its energy absorbing landing gear. The OH-58D is a light scouting aircraft; it carries no loads but a wider

range of weapons, and must land lightly on its skids. As the data shows, the different designs and mission profiles of these two aircraft result in different dynamic environments. The large differences show the importance of considering aircraft-specific data when tailoring a discrimination algorithm.

Crash Kinematics

The U.S. Army Safety Center (USASC) performs post-crash investigations and maintains accident records for Army helicopters. Studies of these records provide useful information such as injury statistics, probabilities of sustaining a crash at different levels of crash severity, and insight into the effectiveness of new safety features. Almost all current knowledge of the kinematics of actual crashes comes from these records. The records reveal that helicopter crashes are often preceded by an initial impact like main or tail rotor contact with power lines, trees, or other obstacles. The ensuing loss of aircraft control can induce sudden unwanted flight maneuvers such as rotation about the main rotor or flipping tail over nose. All of these events usually occur before major impact with the ground. Crash sensing systems must be able to differentiate these events from the major ground impact to avoid inflating prematurely and decreasing the effectiveness of the inflatable restraints. The entire accident sequence can extend for several seconds with pre-crash flight dynamics followed by sliding, rolling, and bouncing on the ground. Multidimensional sensing is required to provide adequate crash discrimination during these complex events.

The location of sensing elements is also an important design decision. Loss of tail rotor thrust is one event that frequently precipitates a crash. When thrust is lost, the aircraft starts to yaw about the main rotor at an increasing rate until the aviators begin the prescribed emergency procedures to reduce the yaw rate and set the aircraft down. Crash sensing elements located away from the spin axis will see a centrepital acceleration that must be considered as a non-crash event and handled appropriately by the discrimination algorithm. Sensors must also be mounted on stiff aircraft structure to ensure accurate transmission of crash accelerations through the structure, with no dynamic amplification or damping effects.

Data Recording

Military crash investigation records provided the vital first-order type estimates of crash loads that were used to design current safety systems. A fuller understanding of the crash dynamics would allow better designs for next generation safety devices. With the rarity of crash testing, perhaps the only way to gather this type of information is crash data recording. Recorded accelerations would also help crash investigators, and would better define the boundary where inflatable restraints are needed, paving the way for developing the kind of advanced discrimination algorithms used by the automotive industry. Current helicopter flight recorders are focused on flight time scales and sample too slowly to record crash accelerations. Recording must be provided by a separate device. Crash sensing units are a perfect candidate because the needed sensors and supporting electronics are already in place. The CABS systems require a full 60 seconds of crash

data recording for these reasons. The recording requirement drives both software and hardware design considerations.

HARDWARE CONSIDERATIONS

Climate

The operating temperature range defines the ambient air temperature extremes between which the equipment must meet all performance requirements. Various military specifications describe worldwide climates and discuss considerations for temperature range selection. The primary tradeoff is choosing a range that will capture the majority of operating time without being so extreme as to require special parts that drive up costs. The location of equipment must be considered when choosing the range limits. Most of the components for inflatable restraints will be located in the cockpit. Cockpit environmental controls maintain a climate suitable for human occupancy. The temperature range of –25 to 130 °F will capture the majority of aircraft operating time for items in the cockpit, and allows use of parts that make the cost-benefit ratio more attractive. The upper end of the range must be extended for items exposed to direct sunlight, and both ends must be extended for items located outside of the cockpit.

Items in the cockpit can also be exposed to extreme temperatures. Arctic kits allow some aircraft to remain fully operational down to –50 °F, and some electrical systems can operate down to –65 °F when the aircraft is first started. The ambient air temperature inside a closed cockpit in direct sunlight can exceed 220 °F in summer. While it is unlikely that cockpit mounted air bags will ever deploy at these extremes, the electronics may be operated there briefly when the aircraft is first started, before the climate controls take effect. Full performance may not be required at the temperature extremes, but the electronics must be able to operate without causing damage or creating an unsafe condition.

Temperature changes occur when the cockpit environmental controls begin to operate, and while the aircraft flies through different altitudes. These induced temperature changes cause thermal expansion and contraction that can fatigue components, opening electrical connections and causing mechanical failures. Electrical properties including resistance and capacitance change with temperature. Many components, such as batteries, are temperature limited and will not function beyond a given range.

The combined effects of temperature, pressure, and humidity can create a condensation cycle that gradually fills electronic assemblies with water. Units must either be properly vented, hermetically sealed, encased in potting compounds, or environmentally sealed with a periodic maintenance cycle to prevent moisture buildup. Cockpits are not always well protected from the weather, and can experience water run-off from rain or condensation. Some flights are made with doors removed (the OH-58D is sometimes flown this way), which can further expose electronics to the surrounding atmosphere. Blowing sand and dust is frequently encountered, especially while landing in desert terrain. Shipboard operations can cause exposure to salt fog that is both highly corrosive

and creates an electrically conductive condensate. Fungus can grow on any nutritive substance in tropical climates. Fuel spills can create an explosive atmosphere that electronics operation must not ignite.

Vibration

The helicopter drive train subjects the entire aircraft to continuous low-level, low-frequency vibrations. The largest amplitudes occur at multiples of the main and tail rotor frequencies. Electronics mounted near the cockpit are dominated by the main rotor, with peak amplitudes at 4.3, 17.2, 34.4, and 51.6 Hz for the UH-60A/L and 6.6, 26.4, 52.8, and 79.2 Hz for the OH-58D. For electronics that must operate in several different aircraft, it is difficult to force resonant frequencies to occur between the driving frequencies of the rotor system. Instead resonant frequencies below about 100 Hz must be completely avoided. Weapons discharge (such as machine gun fire and rocket launches) introduces higher amplitude, higher-frequency vibrations that occur infrequently. Both engine and weapons vibrations can loosen fasteners and fatigue structural supports within devices, leading to mechanical failures. Dynamic amplification effects on circuit cards can lead to false acceleration measurements that make proper discrimination difficult.

Electromagnetic Effects

Electromagnetic environmental effects (E^3) can cause malfunctions and failures in electronic equipment that can prevent its operation or lead to unsafe conditions. Grounding and shielding provisions must be designed to protect the equipment. Military aircraft electronics are tested in a variety of different electromagnetic environments to ensure correct operation under all conditions that can occur in the field. The E^3 threat is different for Army, Air Force, and Navy aircraft, and test levels are set accordingly to avoid over-designing and increasing costs. Electronics that must operate in several different aircraft must be designed to meet the worst case conditions for all. Designs are evaluated through extensive bench top and aircraft level E^3 tests including conducted and radiated electromagnetic interference, electrostatic discharge, compatibility with other equipment, susceptibility of electric initiators to inadvertent activation, and lightning effects (MIL-STD-464).

Reliability and Maintainability

Reliability requirements dictate how often the crash sensing system must deploy the air bags when needed, and how often it can deploy when not needed. These requirements drive the hardware and software design and selection of components. For the CABS, the system reliability requirement for air bag deployment in a crash has been established at 0.999. The system reliability requirement for inadvertent deployment, defined as deployment when the criteria for a crash have not been met, has been established at 1.0×10^{-9}, which corresponds to the Federal Aviation Administration requirement for a catastrophic failure condition. The crash sensing components must meet better reliability numbers for the entire system to pass. Approaches to meet the requirements include

selecting components with high inherent reliability, implementing backup systems for hardware redundancy, and providing software mitigation of failures. Often a combination of these approaches proves most effective. Reliability analysis and testing are conducted to confirm that the design has met the reliability goals. Some inadvertent deployment design requirements and mitigation approaches are discussed in a recent paper (Sprague, 1999).

Minimizing maintenance time reduces the cost of owning systems like inflatable restraints. Crash sensing systems must provide built-in self-tests for quick problem diagnosis, and automatic fault isolation to identify bad components, allowing maintainers to find the source of trouble without searching. An overall status indicator is needed to allow quick pre-flight checks of system operability. Quick attach connectors and captive mounting hardware are needed for rapid installation and removal of components when replacement is required.

Backup Power

Sensing systems cannot rely on the aircraft power system. Initial aircraft damage during a crash can occur several seconds before ground impact, possibly cutting off the crash sensing system from aircraft power. Some emergency procedures, like response to an electrical fire, require the aviators to shut down power. Sensing units must store energy internally to activate air bag deployment, and provide their own backup power for a significant amount of time. The CABS designs were required to incorporate 30 seconds of full functionality after loss of aircraft power. The time is based on descent rates and the accident records which show that most severe crashes occur while flying at low altitudes (several hundred feet or less). When the aviators have more altitude to work with, they have time to induce autorotation and can often complete a controlled impact resulting in no injuries.

Batteries would traditionally be needed to meet this backup power requirement. But batteries cause logistics headaches, and the military has strongly discouraged the introduction of new batteries into their inventory. And no existing battery can meet the reliability requirements under the entire required temperature range. Whatever method is used for backup power must also fit within the size and weight constraints. Helicopters are packed tightly with equipment and space can be limited. Weight is a major design consideration for aircraft. The CABS crash sensing system has been limited to less than 3 lb.

CONCLUSIONS

Recent work on the design and development of military supplemental restraint systems has led to a much fuller understanding of the design considerations for effective crash sensing. High reliability systems with good performance can now be fielded with confidence. The understanding of design needs will continue to evolve as feedback from fielded systems is incorporated into next generation designs.

ACKNOWLEDGEMENT

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BIOGRAPHY

Mr. Gansman has worked on inflatable restraints at Simula for three years in the areas of system level design, crash sensing, and injury assessment. Previously he worked five years in computational fluid dynamics, heat transfer, and combustion system design for the Babcock and Wilcox Company. He holds an M.S. and B.S. in Mechanical Engineering from North Carolina State University.

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An Objective Evaluation of the Potential for Inadvertent CABS Deployment

Michael Happ
Program Manager
H. Koch & Sons Co.
5410 E. La Palma Avenue
Anaheim, CA 92807

ABSTRACT

The DOD's CABS Program has significant potential to reduce deaths and serious injuries in survivable aviation crashes. In particular, the original CABS ECSU (developed by H. Koch & Sons Co.) has demonstrated remarkable crash-recognition performance. Koch's ECSU has repeatedly detected, interpreted, and *correctly* responded to all tested crash events (actual, engineered, and simulated).

However, under certain noncrash conditions, the CABS ECSU crash-discrimination algorithm is *suspected* to be potentially vulnerable, causing inadvertent CABS deployment. These noncrash phenomena are known to exist and could cause system actuation **IF** the magnitude and duration of the measured accelerations produce a change in velocity in excess of the predefined parameters, or thresholds, for crash-recognition.

Safety systems, like all technological systems, must continue to evolve. This paper presents several hypothetical, noncrash conditions and evaluates the potential for the ECSU software algorithm to inadvertently deploy the CABS. This paper intends to either resolve the issue of potential inadvertent system actuation (by validating the current CABS software algorithm) or expose the current weakness(es) for preventing inadvertent system actuation, leading to the requirement for an enhanced CABS ECSU software algorithm. The ultimate goal is realization of the full potential of cockpit airbags to the benefit of military aviators.

INTRODUCTION

The DOD's Cockpit Airbag System (CABS) Program* has significant potential to reduce deaths and serious injuries in survivable aviation crashes. The original CABS ECSU (developed by H. Koch & Sons Co.) has demonstrated remarkable crash-recognition performance. Koch's ECSU has repeatedly detected, interpreted, and *correctly* responded to all tested crash events (actual, engineered, and simulated).

Figure 1 shows the vertical-direction (aircraft coordinate system) acceleration pulse (near the floor of the pilot's seat) from an actual crash test[1] of a full-scale CH-47 airframe at NASA-Langley in August 1976. This acceleration pulse is presented as typical/representative of the true crash environment. Employing the CABS vertical thresholds for the UH-60A/L aircraft[†], the current ECSU crash-recognition software algorithm[2] measures and filters this data, producing a small phase delay, as shown in Figure 1. The algorithm also interprets this data (i.e., computes the change in velocity) as a crash event, correctly initiating CABS deployment (shown graphically by the ECSU actuation value going from 0.0 to 30.0) at 33.2 msecs.

However, speculation on the *potential* for inadvertent CABS deployment has plagued the ECSU since the beginning of the CABS program. That is, certain **noncrash** acceleration pulses could potentially be interpreted as actual crashes, incorrectly actuating the CABS, and creating a potentially dangerous cockpit scenario. Such noncrash events suspected of making the

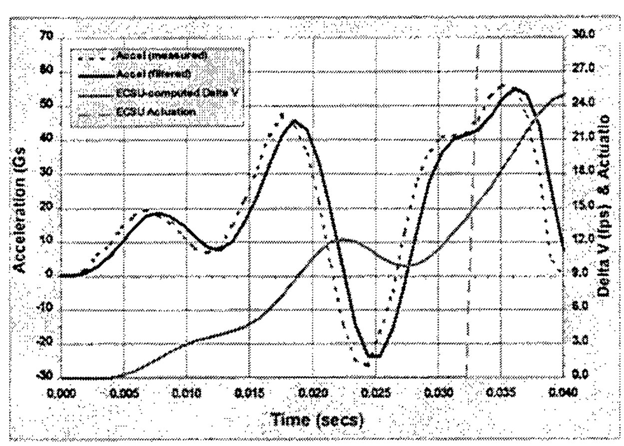

Figure 1. Example CABS ECSU Algorithm Operation: Actual CH-47 Crash Test Data.

* The CABS Program is a multi-service (Army, Navy, Air Force, Marines, Coast Guard, NASA and FAA) development effort to incorporate airbag technology into military helicopters and, eventually, other aviation vehicles.

† The CABS vertical thresholds for the UH-60A/L aircraft (5.0 Gs and 15 fps) are used for this discussion because no thresholds are known to exist for the CH-47 aircraft.

ECSU vulnerable to inadvertent CABS actuation are commonly referred to as (1) a "hammer strike", (2) an accelerometer failure, or (3) a hard landing*. However, no analytical evaluation has ever been performed to substantiate or refute this assumption. The potential for inadvertent CABS deployment actually reflects the design of the *software* algorithm[2]; there are no known/suspected *hardware* design issues.

The hammer-strike phenomenon can be caused by any activity that produces a jarring motion to an "operational" ECSU (power applied, self-tests completed, crash-recognition algorithm active). Potential examples of hammer-strike-like acceleration profiles are (a) maintenance performed by ground personnel (i.e., dropping, or use of, a tool near the ECSU; this activity may be totally unrelated to the ECSU or CABS), (b) any heavy object dropped on the cockpit floor near the ECSU installation location, and (c) ECSU being kicked.

Early in the CABS development, a hammer strike was loosely defined as any short-duration acceleration pulse, <u>less than 5 msecs in duration</u>, and typically in excess of 20 Gs, as shown in Figure 2a. However, the actual amplitude and duration of a hammer-strike-like acceleration profile can vary tremendously depending on the actual event causing the acceleration pulse, the impact proximity to the ECSU mounting location, and the inherent fuselage structural damping between the point of impact and the ECSU mounting location.

An accelerometer failure would typically result in the measured acceleration jumping to a +/- full-scale value (i.e., +/- 50 Gs) very rapidly, typically in one or two samples, as shown in Figure 2b. Currently, on power-up, the ECSU performs a self-test of each accelerometer to ensure proper operation. However, after that point, proper accelerometer operation cannot be verified without suspending the crash-recognition algorithm for 30 msecs

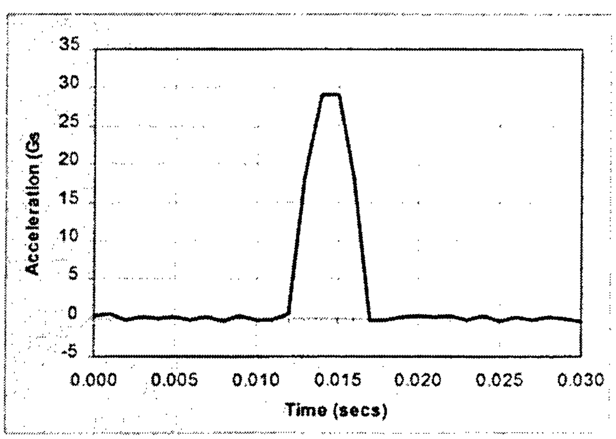

Figure 2a. Example of Hammer-Strike Phenomena.

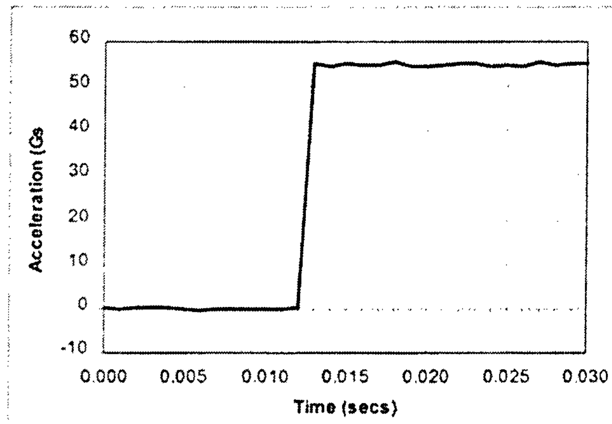

Figure 2b. Example of Accelerometer-Failure Phenomena.

(10 msecs for each of three accelerometers) per duty cycle (dependent on the desired frequency of accelerometer self-tests). If a crash were to occur during an accelerometer self-test, the ECSU may be unable to recognize it. For this reason, ECSUs produced to date provide no "operational" accelerometer-failure safeguards.

Although these noncrash events are considered extremely rare, the *possibility* of occurrence warrants serious analysis, evaluation, and possible implementation of software methods to preclude inadvertent CABS deployment. Currently, as a rudimentary attempt to preclude hammer strikes, a programmable inhibit constraint (referred to as the "lower reset time limit"[2]), currently 5 msecs, was implemented in the ECSU software algorithm[2] due to the defined nature of the hammer-strike acceleration profile (namely, a pulse width of 5 msecs or less). In the ECSU algorithm, once the integrator has been activated by an acceleration threshold exceedence, **IF** the change-in-velocity threshold is exceeded (a requirement for CABS deployment) in less than 5 msecs, the actuation signal is overruled, and the algorithm resets.

Based on this approach, however, an acceleration profile achieving the requisite change in velocity for CABS deployment in 6 msec is, by definition, a crash, and NOT a hammer strike. Likewise, a crash with a high acceleration-onset rate may be interpreted as a hammer strike rather than a crash **IF** the change-in-velocity threshold is exceeded in less than 5 msecs. Furthermore, as previously mentioned, no method is employed to preclude CABS deployment due to an accelerometer failure <u>after</u> the initial (power-up) self-test.

Therefore, the real issues are: Do the current levels of software safeguards implemented within the ECSU algorithm (1) allow inadvertent CABS actuation from noncrash phenomena? and (2) prevent CABS actuation during real crashes? Furthermore, can the software algorithm be made "smart" enough to detect and properly handle these abnormalities without affecting the current crash-recognition capabilities?

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* A hard landing is a noncrash event that can and should be addressed by the proper definition of the acceleration and change-in-velocity thresholds for each aircraft and, therefore, is omitted from this discussion.

DISCUSSION

The discussion of how the ECSU algorithm handles acceleration profiles can quickly get very convoluted. Thus, to ensure understanding without affecting the validity of the results, the following simplifications are employed:

- All acceleration data is "single-axis"; however, the analysis applies equally to omni-directional (3D) acceleration profiles *provided* all exponents are 2.0.
- A 1024-Hertz cycle frequency is assumed, as employed in the Koch ECSU.
- Although for most of the cases presented herein the mathematically idealized acceleration profile is synchronized to the ECSU sampling, in actuality, ECSU sampling is asynchronous to the acceleration pulse.
- A +/- ½-G random noise (somewhat conservative) is superimposed on the mathematically idealized acceleration profile to represent real-life conditions, emulating the actual operation of the Koch ECSU.
- The mathematically idealized acceleration profile (with noise) is filtered (mathematical equivalent of the anti-aliasing, 275-Hz, 2-pole, low-pass hardware filter implemented within the Koch ECSU), again emulating actual ECSU operation.
- The assumed ECSU acceleration threshold* (A_t) is 3.5 Gs, and the assumed change-in-velocity threshold* (ΔV_t) is 2 fps. Although these values are the lowest CABS thresholds used to date (actual Apache lateral-direction thresholds), they represent the most likely scenario for inadvertent CABS deployment.

Since the exact characteristics of a hammer strike (as discussed previously) are unknown, all possible parameters, no matter how ludicrous, must be considered. Experience has shown that reality is a far more creative villain when it comes to unusual acceleration profiles. Thus, the job of differentiating hammer strikes from actual crashes is very difficult. Five hypothetical hammer-strike cases are presented to illustrate this point.

* These thresholds are preprogrammed for each aircraft by the ECSU manufacturer to CABS specifications established by DoD, and are (or can be) different in each of the six direction-specific aircraft coordinates. In many aircraft, some directional thresholds are intentionally set very low to ensure faster CABS deployment for crashes in those particular directions. Unfortunately, this approach also increases the potential for inadvertent CABS deployment.

Case #1a: A 55-G, 2-msec Hammer Strike

A 55-G, 2-msec half-sine-wave pulse is the maximum-amplitude (based on the performance characteristics of the accelerometers employed), minimum-duration pulse that can theoretically occur. (This pulse actually fits the defined parameters for a hammer strike as well as an accelerometer failure.) Although such a pulse may never occur, the pulse characteristics are feasible and, therefore, the possibility of occurrence cannot be ruled out. The maximum, theoretical change in velocity (ignoring the component lost prior to the acceleration exceedence threshold) for this acceleration profile is 2.25 fps ($> \Delta V_t = 2$ fps).

Figure 3 shows that the ECSU measures this pulse as a 55-G, 2-msec triangular-wave pulse (due to the finiteness of sampling). The maximum, theoretical change in velocity is thus reduced to 1.77 fps ($< \Delta V_t = 2$ fps). Furthermore, the pulse is then effectively attenuated and lengthened by the ECSU filtering into a 29-G, 3.7-msec triangular-wave pulse. The maximum, theoretical change in velocity for this acceleration profile is 1.72 fps ($< \Delta V_t = 2$ fps). In this case, the current ECSU algorithm correctly interprets this data as a noncrash event (ECSU actuation value stays at 0.0), computing the change in velocity to be approximately 1.5 fps (accounting for the component lost prior to the acceleration exceedence threshold).

For this pulse, the maximum change in velocity actually occurs when there is exactly a ½-sample phase shift between the actual accelerations and the ECSU-sampled accelerations. In this case, the maximum, theoretical change in velocity is 2.44 fps ($> \Delta V_t = 2$ fps). Figure 4 shows that the ECSU measures this pulse as a 38.9-G, 2.9-msec trapezoidal-wave pulse (due to the finiteness of sampling). The pulse is then effectively attenuated and lengthened by the ECSU filtering into a clipped 30-G, 4.6-msec haversine-wave pulse. The maximum, theoretical velocity change for this acceleration profile is 2.75 fps ($> \Delta V_t = 2$ fps). In this case, the current ECSU algorithm correctly interprets this

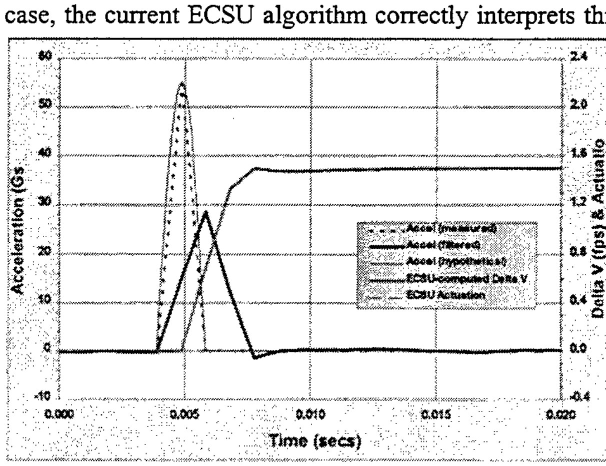

Figure 3. Hypothetical Case #1a: A 55-G, 2-msec Hammer Strike.

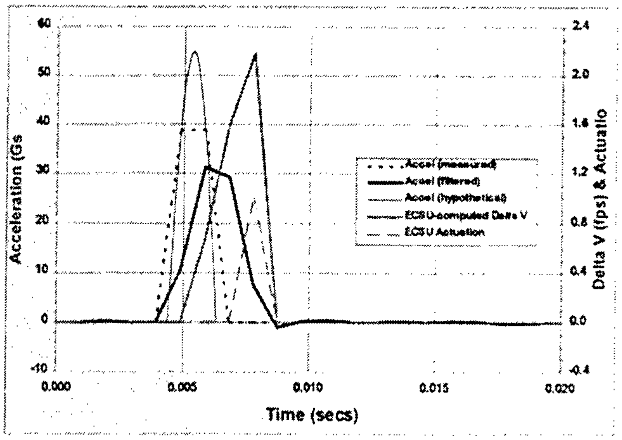

Figure 4. Hypothetical Case #1a: A 55-G, 2-msec Hammer Strike with Phase Shift.

data as a hammer strike (a noncrash event), since the computed change in velocity exceeded 2 fps in less than 5 msecs (ECSU actuation value goes to 1.0), resetting the algorithm (disabling the change-in-velocity calculations until another acceleration exceedence occurs).

Therefore, the 55-G, 2-msec hammer strike is not a threat to inadvertent CABS actuation *because of the internal ECSU filtering* **and** *the implementation of the 5-msec "lower reset time limit"* in the ECSU software algorithm. In addition, larger amplitude acceleration pulses would produce exactly the same result, since the ECSU accelerometers cannot measure above 55 Gs.

Case #1b: A 20-G, 4.9-msec Hammer Strike

A 20-G, 4.9-msec half-sine-wave pulse yields a maximum, theoretical change in velocity (ignoring the component lost prior to the acceleration exceedence threshold) of 2.01 fps ($\approx \Delta V_t$ = 2 fps). This pulse is essentially the maximum-duration hammer-strike pulse that can theoretically occur without firing. Although such a pulse is highly unlikely, the pulse characteristics are feasible and, therefore, the possibility of occurrence cannot be ruled out.

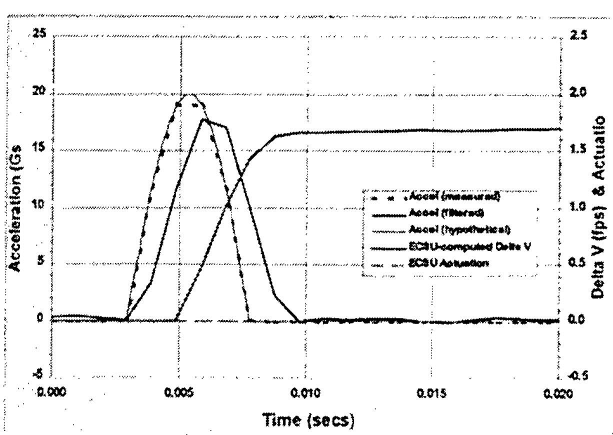

Figure 5. Hypothetical Case #1b: A 20-G, 4.9-msec Hammer Strike.

Figure 5 shows that the ECSU measures this pulse as a "clipped" sine wave, with an amplitude of 19 Gs (due to the finiteness of sampling) and a pulse width of 4.9 msec. The maximum, theoretical change in velocity is thus reduced slightly to 1.99 fps ($\approx \Delta V_t$ = 2 fps). Furthermore, the ECSU filters the pulse leaving it resembling more of a clipped haversine pulse, with an amplitude of 17.5 Gs and a pulse width of 6.6 msec, no longer fitting the loose definition of a hammer strike (it is assumed that the 5-msec duration was intended to be applied to the pre-filtered acceleration data). The maximum, theoretical change in velocity for this acceleration profile is 2.08 fps (> ΔV_t = 2 fps).

In this case, the current ECSU algorithm interprets this data as a noncrash event, computing the velocity change to be approximately 1.68 fps (accounting for the component lost prior to the acceleration exceedence threshold). Thus, the 20-G, 4.9-msec hammer strike is also not a threat to inadvertent CABS actuation due to the internal ECSU filters, *regardless of the implementation of the "lower reset time limit"* in the software algorithm.

Case #1c: A 25-G, 4.9-msec Hammer Strike

By scaling the results from the prior case, a 25-G, 4.9-msec half-sine-wave pulse is likely to produce enough change in velocity to provide a true test for the implementation of the 5-msec "lower reset time limit" in the ECSU software algorithm. This pulse provides a maximum, theoretical change in velocity (ignoring the component lost prior to the acceleration exceedence threshold) of 2.51 fps (> ΔV_t = 2 fps). Although such a pulse is highly unlikely, the pulse characteristics are feasible and, therefore, the possibility of occurrence cannot be ruled out.

Figure 6 shows that the ECSU measures this pulse as a "clipped" sine wave, with an amplitude of 24 Gs (due to the finiteness of sampling) and a pulse width of 4.9 msec. The maximum, theoretical change in velocity is thus reduced slightly to 2.49 fps (> ΔV_t = 2 fps). Furthermore, the ECSU filters the pulse leaving it

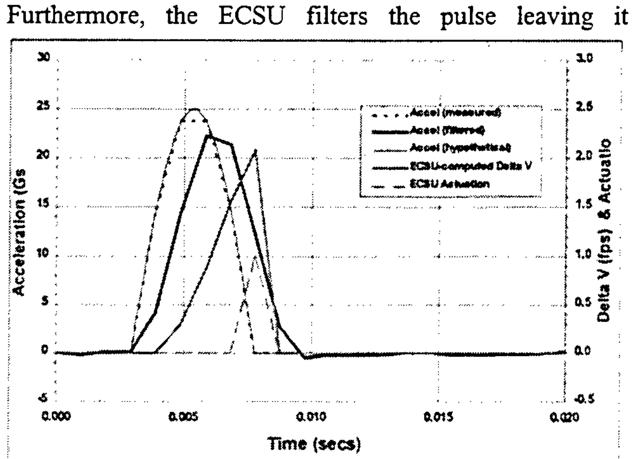

Figure 6. Hypothetical Case #1c: A 25-G, 4.9-msec Hammer Strike.

resembling more of a haversine pulse, with an amplitude of 21.5 Gs and a pulse width of 6.6 msec. The maximum, theoretical change in velocity for this acceleration profile is 2.60 fps (> ΔV_t = 2 fps).

In this case, the current ECSU algorithm correctly interprets this data as a hammer strike (a noncrash event), since the computed change in velocity exceeded 2 fps in less than 5 msecs (ECSU actuation value goes to 1.0), resetting the algorithm (disabling the change-in-velocity calculations until another acceleration exceedence occurs). Thus, the 25-G, 4.9-msec hammer strike is also not a threat to inadvertent CABS actuation *because of the implementation of the 5-msec "lower reset time limit"* in the ECSU software algorithm. In addition, larger amplitude pulses would produce exactly the same result.

Case #1d: A 21-G, 4.9-msec Hammer Strike

Considering the data from the prior case, what if the magnitude of the acceleration pulse were slightly lower -- can the change-in-velocity calculation reach 2.0 just after the 5-msec cutoff? Half-sine-wave pulses with a pulse width of 4.9 msecs and amplitudes of 21-24 Gs were used to test the hypothesis for this case, with an alarming realization. At 21 Gs, the maximum, theoretical change in velocity (ignoring the component lost prior to the acceleration exceedence threshold) is 2.11 fps (> ΔV_t = 2 fps). Again, although such a pulse is highly unlikely, the pulse characteristics are feasible and, therefore, the possibility of occurrence cannot be ruled out.

Figure 7 shows that the ECSU measures this pulse as a "clipped" sine wave, with an amplitude of 19.9 Gs (due to the finiteness of sampling) and a pulse width of 4.9 msec. The maximum, theoretical velocity change is thus reduced somewhat to 2.09 fps (> ΔV_t = 2 fps). Furthermore, the ECSU filters the pulse leaving it resembling more of a haversine pulse, with an amplitude of 18.6 Gs and a pulse width of 6.6 msec. The maximum, theoretical velocity change for this acceleration profile is 2.19 fps (> ΔV_t = 2 fps).

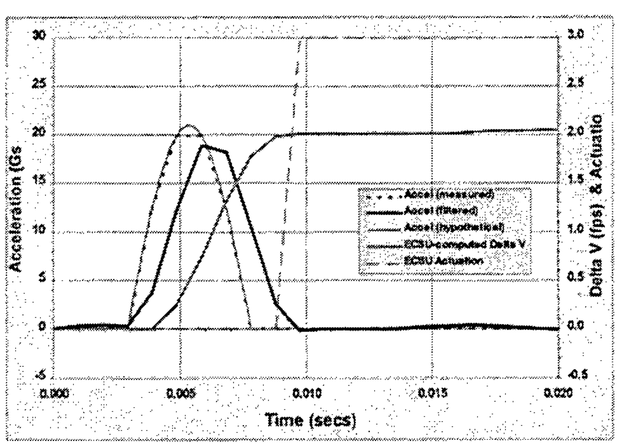

Figure 7. Hypothetical Case #1d: A 21-G, 4.9-msec Hammer Strike.

In this case, the current ECSU algorithm interprets this data as a CRASH event (ECSU actuation value goes to 3.0), since the computed change in velocity exceeded 2 fps just after the 5-msec cutoff. In fact, the randomness of the system noise is a factor here -- 25% of all cases tried with this acceleration pulse yielded system actuation. The following distribution was ascertained:

Pulse Amplitude	Cases Yielding Inadvertent Actuation
20.5 Gs	3%
21.0 Gs	25%
21.2 Gs	33%
21.5 Gs	25%
22.0 Gs	0%

Bottom Line: This type of hammer strike profile **IS** a potential threat for inadvertent CABS deployment.

Case #1e: A 19-G, 5.9-msec Half-Sine-Wave Pulse

The next question to ask is what about a 6-msec acceleration pulse -- is it a hammer strike or a crash? By CABS definition, it is a crash. Period. But, how does the algorithm handle it? Some example cases using half-sine-wave pulses with a pulse width of 5.9 msecs and amplitudes from 17-21 Gs were used to test the hypothesis for this case, again with distressing results. For a 19-G pulse magnitude, the maximum, theoretical change in velocity (ignoring the component lost prior to the acceleration exceedence threshold) is 2.28 fps (> ΔV_t = 2 fps). Again, although such a pulse is highly unlikely, the pulse characteristics are feasible and, therefore, the possibility of occurrence cannot be ruled out.

Figure 8 shows that the ECSU again measures this pulse as essentially a sine wave (with small deviations near the peak due to the finiteness of sampling). The maximum, theoretical velocity change is, for all practical purposes, unchanged. Furthermore, the ECSU filters the pulse leaving it resembling more of a haversine pulse, with an amplitude of 17.8 Gs and a pulse width of 7.7 msec. The maximum, theoretical velocity change for

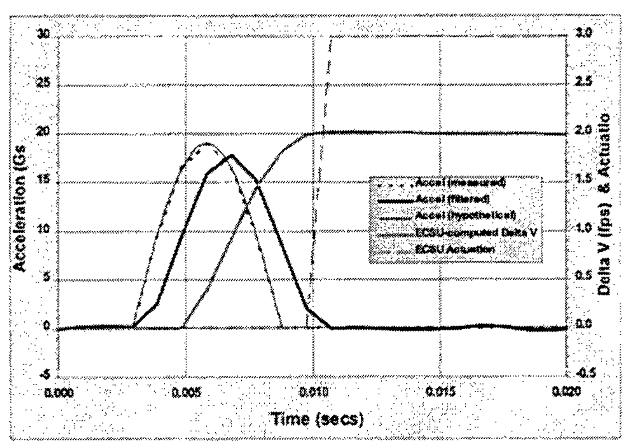

Figure 8. Hypothetical Case #1e: A 19-G, 5.9-msec Half-Sine-Wave Acceleration Pulse.

this acceleration profile is 2.20 fps (> ΔV_t = 2 fps). In this case, the current ECSU algorithm interprets this data as a CRASH event, since the computed change in velocity exceeds 2 fps just after the 5-msecs cutoff. However, again the randomness of the system noise is a factor here -- 60% of all cases tried with this acceleration profile yielded system actuation, as shown below:

Pulse Amplitude	Cases Yielding CABS Actuation
18.0 Gs	0%
18.5 Gs	4%
19.0 Gs	60%
19.5 Gs	10%
20.0 Gs	0%

Perhaps even more surprising from the above table is the percentage of cases that did NOT cause system actuation. Given the fact that all of these pulses are (by definition) crash pulses, one would expect them all to cause system actuation. However, pulse amplitudes of 18 Gs and below simply do not provide enough change in velocity, and pulse amplitudes of 20 Gs and above create too much velocity change too fast (i.e., 2 fps is reached prior to 5 msecs, and they are interpreted as hammer strikes). This result is presented herein as neither good or bad, it simply is the way the algorithm works. Bottom Line: Acceleration pulses with these characteristics may or may not cause CABS actuation -- but should they?

The last case highlights another potential problem -- Can the 5-msec lower reset time limit cause the algorithm to interpret a severe crash as a hammer strike? Specifically, the decision of whether the pulse is a hammer strike or a crash is made from computing the velocity change during *the first six acceleration samples after acceleration threshold exceedence* without any knowledge of the actual pulse shape. Several different approaches were used here to determine conditions where the algorithm might incorrectly interpret the pulse as a hammer strike: (1) the maximum acceleration amplitude for a square wave, (2) the maximum acceleration onset rate (jerk) for a crash pulse with a large linear ramp up, and (3) a "severe" crash pulse (an actual crash pulse with a large acceleration onset rate and a half-sine-wave ramp up).

Case #2a: Square Waves

For a square-wave acceleration pulse, the maximum, theoretical acceleration that will cause a 2-fps change in velocity in 5.9 msecs is 10.5 Gs. Due to the ECSU filtering, and the component lost prior to the acceleration exceedence threshold, the acceleration amplitude of interest will be somewhat higher. Again, although a square-wave acceleration pulse is highly unlikely, the pulse characteristics are feasible and, therefore, the possibility of occurrence cannot be ruled out. In particular, an accelerometer failure (after the ECSU power-up self-test) would likely present a waveform of this type.

Figure 9 shows a 14.25-G, square-wave acceleration pulse. The ECSU measures this pulse as having a trapezoidal front end (due to the finiteness of sampling). Furthermore, the ECSU filters the pulse leaving it resembling a crude haversine pulse in the beginning, until the filter settles. The current ECSU algorithm interprets this data as a hammer strike, since the computed velocity change exceeds 2 fps within the 5-msec window. In fact, the algorithm will continue to reset approximately every 7 msecs until the acceleration pulse is removed (or reduced in amplitude). The randomness of the system noise is again a factor here:

Pulse Amplitude	Cases Interrupted By 5-msec Reset	Cases Yielding CABS Actuation
14.0 Gs	7%	93%
14.25 Gs	37%	63%
14.5 Gs	94%	6%

Thus, square-wave pulses with amplitudes of 14.7 Gs or more create too much change in velocity too fast (i.e., 2 fps is reached prior to 5 msecs, repeatedly), and they are effectively treated as hammer strikes. An accelerometer failure is likely to be in this category, effectively rendering the ECSU inoperable (but NOT causing inadvertent CABS actuation*). Square-wave pulses with amplitudes of 13.9 Gs or less WILL cause CABS actuation. Furthermore, square-wave pulses with amplitudes below 3.5 Gs cannot activate the integrator and, therefore, are ignored. Bottom Line: A square-wave acceleration pulse may actuate the CABS system, depending upon the amplitude.

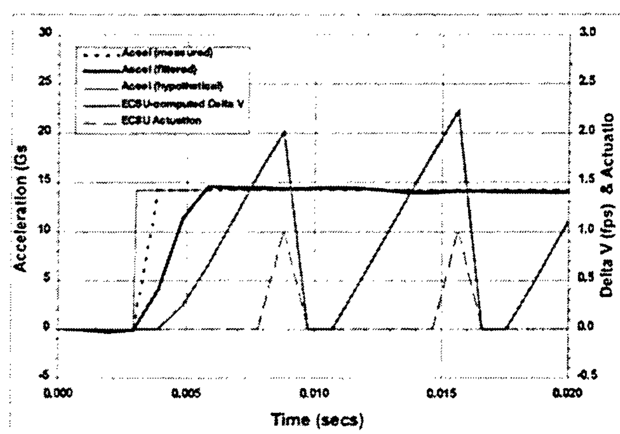

Figure 9. Hypothetical Case #2a: A 14.25-G Square-Wave Pulse.

* This result is unique to the low velocity-change threshold used (2.0 fps). For ΔV_t greater than 8 fps, an accelerometer failure will produce CABS actuation, since the 5-msec limit will no longer inhibit actuation (assuming a correct modeling of the accelerometer-failure event).

Case #2b: Linear Ramp Up

For a linearly increasing (ramp) acceleration pulse, the acceleration onset rate (or jerk) is used. The theoretical point at which the algorithm transitions from interrupting (due to the 5-msec limit) and CABS actuation was computed to be 2486 Gs/sec (ignoring the component lost prior to the acceleration exceedence threshold). Due to the ECSU filtering, and the component lost prior to the acceleration exceedence threshold, the actual jerk transition point is higher. By a trial-and-error approach, the actual transition was found to occur near 2850 Gs/sec. Again, although a linear-ramp acceleration pulse is highly unlikely, the pulse characteristics are feasible and, therefore, the possibility of occurrence cannot be ruled out. In particular, a sine wave mimics this acceleration form during the first $^1/_3$ of the pulse. Furthermore, a severe crash would likely present this type of waveform, particularly during the initial (or secondary) impact.

Figure 10 shows a 2840-Gs/sec-onset acceleration pulse. The ECSU filters the pulse, creating a slight time delay. In this case, the acceleration rises from approximately 6.5 Gs to 20.5 Gs in the first 5 msecs after acceleration threshold exceedence. The current ECSU algorithm interprets this data as a hammer strike, since the computed change in velocity exceeds the threshold value (2 fps) within the 5-msec window. In fact, the algorithm will continue to reset approximately every 7 msecs until the acceleration pulse is removed. The following distribution was ascertained:

Jerk Rate (Gs/sec)	Cases Interrupted By 5-msec Reset	Cases Yielding CABS Actuation
2800	7%	93%
2820	40%	60%
2840	60%	40%
2860	77%	23%
2880	83%	17%
2900	100%	0%

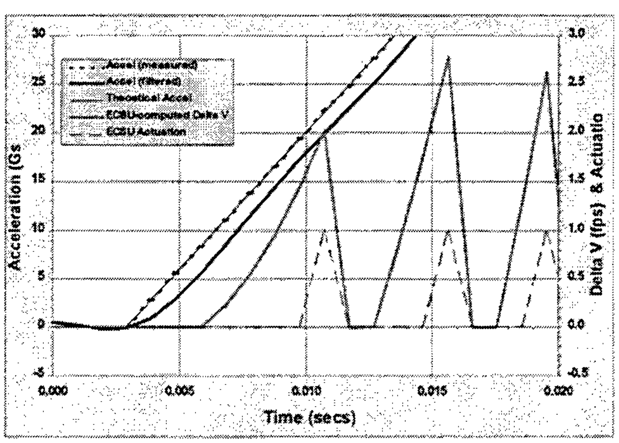

Figure 10. Hypothetical Case #2b: A 2840-Gs/sec Linear-Ramp Acceleration Pulse.

Thus, crash pulses with rapid acceleration onset (jerks) of 2900 Gs/sec or more will create too much change in velocity too fast (i.e., 2 fps is reached prior to 5 msecs, repeatedly), and they are effectively treated as hammer strikes*. Therefore, in severe crash scenarios, the lower reset time limit can interfere with the normal crash-recognition process, delaying CABS deployment. Linear-ramp acceleration pulses with onset rates of 2800 Gs/sec or less will cause CABS actuation* (ignoring cases with very low onset rates as unrealistic for actual crash scenarios). Bottom Line: Linear-ramp acceleration pulses may interfere with proper CABS deployment, depending on the magnitude of the acceleration onset rate.

Case #2c: Severe Crash Pulse

From the previous case, the question now is: How does the algorithm handle an actual severe crash? To investigate this question, the same acceleration pulse shown in Figure 1 was used (from an actual crash test[1] of a full-scale CH-47 airframe at NASA-Langley in August 1976). This Pulse (Figure 11) is ***expected*** to be representative of the actual aircraft crash environment. Although this acceleration profile is for the vertical direction, it could reasonably occur in any direction, or any combination thereof.

Employing the minimum CABS lateral thresholds, the current ECSU algorithm first interprets this data as a hammer-strike event (too much change in velocity too fast; ECSU actuation value goes to 1.0), and resets the algorithm. Then the algorithm interprets the remainder of the pulse data as a crash event. However, note that there is a resultant lag in the CABS deployment time. This result is presented herein as neither good or bad, it simply is the way the algorithm works. Bottom Line: Actual crash pulses may be inhibited, or delayed, from firing by the 5-msec reset limit depending on the impact severity.

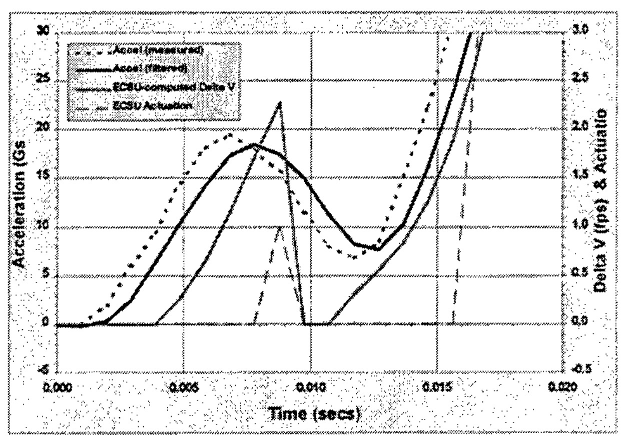

Figure 11. Hypothetical Case #2c: Actual CH-47 Crash Test Data.

* Again, this result is unique to the low value used for the change-in-velocity threshold (ΔV_t) and will be different for other threshold values.

CONCLUSIONS

The CABS crash-recognition algorithm employed in the ECSU works remarkably well in the vast majority of cases. Although rare, however, there are a few anomalies where the ECSU may deploy the CABS in response to certain noncrash events. Similarly, there are some anomalies where CABS deployment is delayed or prevented for certain severe crash events. Both types of anomalies are the direct result of implementation of the 5-msec lower reset time limit.

From the analysis presented herein, it should be obvious that simply increasing the lower reset limit (a parameter that is currently user programmable) will NOT produce the desired effect. While increasing the lower reset limit will help in the case of hammer strikes, it increases the potential for inhibiting or delaying CABS deployment during real crashes. Likewise, using different lower reset limits for each axis is of marginal value since it doesn't address the inherent problem.\\ in particular, make the CABS vulnerable to inadvertent deployment. When the ECSU is active and functioning, the ECSU ***CAN*** inadvertently actuate the CABS under some circumstances IF the resultant, ***filtered*** magnitude and duration of the measured accelerations result in an exceedence of the predefined crash-recognition thresholds (change in velocity). However, the ill-defined nature of hammer strikes and accelerometer failures makes the task of software safeguards extremely difficult. The potential for inadvertent CABS deployment is REAL, and these anomalies represent a real danger to the aircrew, as well as the ground crew.

Now that the speculation regarding the potential for inadvertent CABS deployment has been verified, rectifying these problems is crucial for CABS credibility, and the future viability of cockpit airbags in aviation vehicles. Safety systems, like all technological systems, must continue to evolve. The evolution of an enhanced ECSU software algorithm, and hence smarter CABS, will permit realization of the full potential of cockpit airbags to the benefit of military aviators.

RECOMMENDATIONS

More advanced software methods are required to eliminate inadvertent CABS deployment from noncrash events, and ensure CABS deployment during real crash events, while maintaining (or perhaps improving) the current ECSU's crash-recognition performance capabilities. To achieve that goal, the following tasks should be performed:

- Actual hammer strikes should be measured in various aircraft cockpits for use in characterizing the acceleration profile for this type of noncrash phenomenon, and for performing more detailed analyses.
- Actual ECSU testing should be performed with the acceleration profiles presented herein to validate the analysis.
- Pending successful verification of this analysis, new software methods or algorithms must be developed to preclude the anomalies presented herein.
- Any new software methods or algorithms must also be analyzed, implemented, tested, and verified to ensure proper CABS performance to all crash and noncrash events (i.e., absence of anomalies).

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BIOGRAPHY

Michael Happ is a Program Manager for H. Koch & Sons Co. (Anaheim, CA) where he supports the research and development of new aviation safety products. He has a B.S. degree in Aeronautical and Astronautical Engineering from the University of Illinois (Urbana, Illinois), an MBA from Florida State University (Tallahassee, Florida), and 20 years of related engineering experience. Mr. Happ led the original CABS ECSU engineering development effort for Koch, which was based on a prior 3-D aviation crash sensor he co-developed while an employee of AST, Inc. He is a current member of the SAFE Association and the Society of Automotive Engineers (SAE).

Vent Control as a Means of Enhancing Airbag Performance

Richard E. Zimmermann
Zerad, Inc.
425 East Greenway Drive
Tempe, AZ 85282-6938

ABSTRACT

Typical automotive airbag systems have a fixed area vent for exiting gasses. The US Army Cockpit Airbag System (CABS) is unvented to prolong the period during which the system can provide occupant protection during extended helicopter crash scenarios. In each application, system performance may be enhanced by providing a controlled vent area. This paper describes work conducted under a Phase I SBIR program sponsored by the NASA Langley Research Center. The work was focused on eventual inflatable restraint system applications in general aviation aircraft, and showed that appropriate vent control offers many enhancements. Two series of tests conducted during Phase I showed that inflatable restraint system size and weight can be reduced without degrading performance, injury potential in an out of position situation (OOPS) deployment can be reduced, and peak bag pressures can be reduced (at any temperature) during normal operation.

INTRODUCTION

The primary project objective was to make occupant protection airbags more efficient by controlling the flow of vented gas. Another objective was to reduce the probability and severity of airbag induced injury in situations where the occupant is initially too close to the deploying airbag. The immediate application of interest was general aviation aircraft, but application to other airbag systems are obvious. Project tasks included valve concept development, preliminary analysis of system performance with the valves, and two series of tests evaluating the performance of a prototype valve assembly.

The valve design must provide rapid initial opening upon occupant contact with the bag as well as appropriate follow on area variation. Other factors considered in a design tradeoff study included the following:

- Functionality: Will a valve using the concept be able to control the flow as required?

- Adaptability: Assuming the valve concept can be used to control the flow, can a product applying the concept be included in a practical airbag module given reasonable weight and volume constraints?

- Durability: Will the components of any product based on the concept remain functional for the life of an airbag module?

- Cost: Can needed components be produced for a cost that will permit their inclusion in an airbag module?

- Ease of Assembly: Can a valve based on the concept be economically installed (OEM and service) in an airbag module?

Various valve concepts were developed, and a tradeoff study was conducted to identify the one must suitable for the airbag application. A detailed design of the preferred configuration was prepared, and a prototype valve assembly was fabricated. The prototype valve provided six 1.25 inch diameter ports, and selectable relief pressures of 3, 4 and 5 psi. The details of the valve design are not disclosed in this paper because the patent application is still in process.

ANALYSIS

Simplified and expedient numerical analyses used in Phase I applied fundamental engineering principles to predict pressure, displacement, and force as a function of time. Use of the simplified analysis in Phase I provided adequate results for supporting preliminary design work, and also conserved Phase I resources, permitting more testing. MATLAB was used for this simplified numerical analysis. More sophisticated analytical tools, such as MSC.DYTRAN, will be used in follow on development to optimize the prototype system designs and predict injury criteria before testing.

The analytical steps used in the analysis were as follows:

- Using initial bag pressure and volume, occupant deceleration was integrated to obtain velocity and displacement.

- The increment of displacement was used to calculate a new bag pressure due to compression.

- Orifice flow equations were used to calculate an increment of mass flow rate, given the vent valve design characteristics.

- The reduction in bag pressure due to the increment of exiting gas flow was calculated.

- The resulting bag volume and gas characteristics were used to calculate a new increment of force on the occupant.

- Incremental calculations for fractions of a millisecond were computed for the total bag compression.

Once the MATLAB model was verified against existing pallet airbag test data it, was used to model the performance of the vent valve concept and assist in the development of the prototype valve.

TEST PROCEDURE

The test procedures were designed to demonstrate the feasibility of using an exhaust vent valve to improve the performance of occupant protection airbags. There were two series of tests: ride-down tests and OOPS tests. The ridedown tests evaluated the performance of the airbag as it performs its normal function of decelerating the occupant's mass during a crash. The OOPS tests evaluated changes in potential airbag induced injury during an out of position situation (occupant too close to airbag during deployment).

Ride-down Tests:

Test Method: The general test method is illustrated in figure 1. A custom made airbag was attached to a housing in which the vent valves were installed. On the other end of the housing, a plate sealed the inflator opening. The housing was installed in a fixture beneath the drop tower, where a weight released from preplanned heights could compress the bag. The airbag was preinflated with compressed air to simulate inflation, and the falling weight compressed the bag to simulate occupant impact. The air bag used in the ridedown tests was cylindrical to approximate the performance predicted by the analysis. Both the diameter and the height of the bag was 16 inches. The deceleration of the weight and the pressure in the bag were measured throughout the event and recorded. Tests were also conducted without vent valves to provide a baseline (representing "as is" auto airbag designs).

Test Matrix: Tests with each of the three vent valve pre-loads (3, 4,and 5 psi) and baseline tests were conducted for nine different conditions. Weights of 30, 60, and 100 pounds were used, and initial velocities were 10, 15, and 22 ft/sec. Free fall drop heights corresponding to the three initial velocities were 1.55, 3.49, and 7.50 feet. A total of 36 different tests were performed.

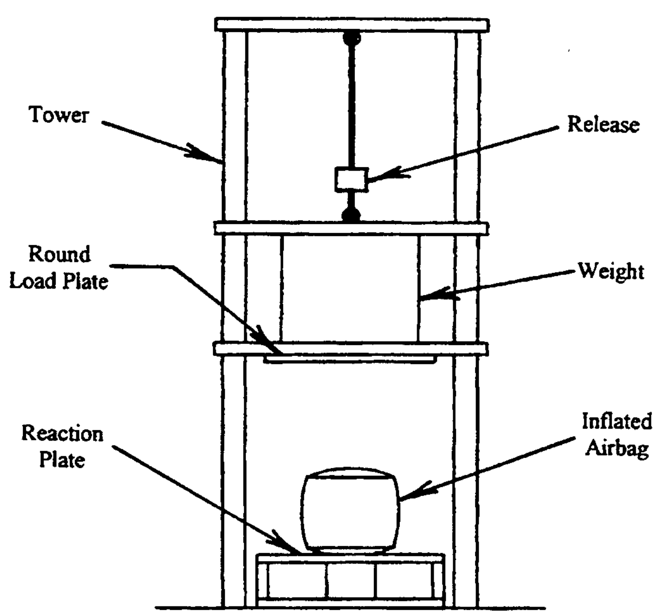

Figure1: Ride-Down Test Setup

Weights: The weights used in the tests simulated the effective weight of the occupant wearing lap belt and single shoulder harness. This effective weight that will load an airbag was estimated at 1/3 of total body weight. This estimate was based on experience and literature showing that an occupant wearing a three-point restraint applies approximately 2/3 of the inertial load to the lap belt restraint. While appropriate for general aviation applications where the occupants will be wearing primary restraints, the same assumptions have not been applied in the design of airbags for automobiles manufactured in the United States. Unlike auto airbags manufactured in Europe, those airbags are required to provide protection even if a primary restraint is not worn (reference 1).

Instrumentation: Two pressure sensors and two accelerometers were used in the ride-down tests. Both accelerometers were mounted on the dropped weight, and both pressure sensors were installed in ports in the valve housing. A small infrared lamp and photosensor were used for a trigger. A small metal flag attached to the fixture with the drop weight passed between the lamp and sensor. The resulting voltage change triggered the data acquisition system. The trigger was positioned on the tower to generate the triggering voltage just before the weight made contact with the airbag.

For the baseline tests, four of the vent valves were clamped tight shut, and air was allowed to exit from two completely open ports. A trip wire was set to release dump valves over the two "open" ports as the falling weight touched the top of the bag. These valves over the "open" ports were used to conserve compressed air. The proper initial pressure could not be achieved in the bag without them. This arrangement successfully simulated a bag prefilled with air as it was vented by a pair of (two) 1.25 in. diameter holes.

For the baseline tests, the vent hole size and number were chosen as typical of existing automotive airbags. For some time, airbags had a vent hole approximately 2 in. in diameter. Some newer bags, apparently of the "depowered" type, have a pair of vents that are each 1 in. in diameter. Therefore, vent area in US auto airbags ranges from 1.5 to 3.1 square inches, and the test setup used a vent area of 2.5 square inches. Page 9 of reference 2 provides information on typical vent areas used in earlier airbag designs.

OOPS Tests:

The OOPS tests were conducted by deploying airbags with a barrier positioned to prevent complete bag inflation.

Test Method: A gas generator was installed in the prototype valve housing which was in turn installed in a test fixture (see figure 2). An airbag was attached to the valve housing, and an adjustable barrier attached to the fixture prevented full deployment of the airbag. The folded airbag was deployed, and bag pressure was measured. This process was repeated for a baseline condition without vent valves. The reduction in peak pressure achieved with the vent valve configuration is an approximate indication of reduced probability and/or reduced severity of airbag induced injury. The tests were repeated with

the barrier positioned at three different distances from the undeployed airbag. The fixture was the same as that used in the ridedown test, but vertical supports were added to mount the barrier.

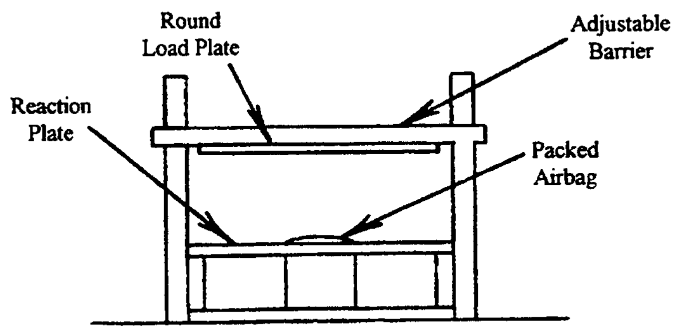

Figure 2: OOPS Test Fixture

The airbags used in this test series were round (28-inch diameter) 60-liter airbags similar to drivers' side airbags used in US automobiles. Tethers were not installed because they would have served no purpose with a barrier obstructing full bag deployment. The bags were folded in a typical automotive fold pattern, and tape was used to approximate the opening force of the plastic enclosure included in production configurations. The bag fabric was 420-denier Nylon 66, plain woven with neoprene coating on one side.

To perform the baseline tests, all vent valves were removed. Four ports were blocked, and the other two ports remained open to simulate the vents in conventional airbags.

The gas generator was ignited by manually closing a switch connected to a 12 VDC auto battery. The inflator was a new non-azide model D 60 automotive inflator provided by Talley Defense Systems of Mesa, Arizona. The inflator is being marketed by a Talley subsidiary called AEGIS Technologies, and is much smaller and lighter than the earlier azide type inflators. The smaller size makes it much more attractive for potential use in a general aviation application.

Test Matrix: Six different types of OOPS tests were conducted. The tests included distances of 4, 8, and 12 in., and were performed with two different valve configurations (vent valve and baseline). The vent valve tests were conducted with the 5 psi pre-load configuration, and the baseline tests were conducted with four ports blocked and two ports open. Each of the six tests was conducted twice to demonstrate repeatability. In addition, two tests were run with the 3 psi pre-load vent valve configuration.

Instrumentation: Two identical pressure sensors were installed in the housing between the airbag and the gas generator.

TEST RESULTS

Results of Ridedown (drop) Tests:

Data in the ridedown tests was collected at 10,000 samples per second and then filtered (post test) with an SAE J211 Class 60 digital filter. The filter software was an MS-Excel implementation of the SAE filter that was provided by The FAA Civil Aeromedical Institute (CAMI). Then, the two pressure and acceleration channels were averaged. Finally, the averaged acceleration was integrated twice to obtain velocity and displacement. The data was averaged, integrated, and plotted with MS Excel 97.

The following tables summarize strokes required to bring the velocity of the falling weight to zero. There is a separate table for the tests with the 100, 60 and 30 pound weight. Each of those tables contains information for the various valve configurations and impact velocities.

Summary of Stroking Distances in Ridedown Tests: The following three tables summarize the average stroke for each valve type and drop height. These results demonstrate feasibility of the concept, but not the ultimate capability of the valve design. No attempt was made to optimize performance in Phase I.

Table 1: Strokes for 100 Pound Weight (inches)

	Valve			
Height (1/100 ft)	3 psi	4 psi	5 psi	baseline
750	12	11.7	11.2	14.3
349	8.5	8	8	11.4
155	6.6	6.4	6.2	10.2

Table 2: Strokes for 60 Pound Weight (inches)

	Valve			
Height (1/100 ft)	3 psi	4 psi	5 psi	baseline
750	12	11.5	8	10
349	10	9.5	6	9
155	9.9	8.6	5	8

Table 3: Strokes for 30 Pound Weight (inches)

	Valve			
Height (1/100 ft)	3 psi	4 psi	5 psi	baseline
750	10	10	10	10
349	8.2	7.8	7.5	8.7
155	7.5	7.6	7.2	7.2

Performance was improved the most with the 60 pound weight. Appropriate adjustment could presumable improve performance for other weights.

Results of OOPS Tests:

The following table shows the average peak pressures obtained in the various tests.

Table 4: Average Peak Pressures for Each Valve Configuration (psi)				
Distance (in.)	Valve			% base/5 psi
	3 psi	5 psi	baseline	
12	N/A	9	14.8	164
8	8.5	7.3	11.4	156
4	N/A	8.6	19.5	226

The following table shows the time the airbag pressure was over 6 psi.

Table 5: Average time over 6 psi – msec				
Distance (in.)	Valve			% base/5 psi
	3 psi	5 psi	baseline	
12	N/A	4.5 msec	6 (msec)	133
8	4 msec	3.5 msec	7.5 (msec)	214
4	N/A	8 msec	N/A	N/A

The last columns in the above two tables show the percentage difference between the baseline condition (two 1.25 in. open ports) and the vent valve with the 5 psi relief pressure.

DISCUSSION

The tests demonstrated that the vent valve can control the flow of exiting gas and shorten the required stroke in a number of ways.

First, the pre-load on the valve can establish the desired pre-charge in the bag at the time of occupant impact. Creating as high a pre-charge pressure as practical is the most effective way to reduce total stroke requirements, because additional deceleration is provided at the time the velocity is highest. However, the benefits of increased initial pre-charge must be traded off against the requirement to limit the potential for injury in an OOPS.

Secondly, the characteristics of the opening (and open) valve can influence the peak acceleration reached during occupant ridedown. A valve with a lower spring constant will open faster, allow gas to escape more quickly, and reduce the peak acceleration. The maximum area of the valve in the full open position also affects the rate of initial gas flow. However, higher peak pressures which limit total stroke must be traded off against injury criteria such as the HIC.

Finally, the valve spring rate can also influence the remaining stroking distance required following peak pressure. If the valve closes faster following peak bag pressure, it keeps bag pressure higher during the final portion of the stroke. This keeps the final acceleration higher, and also contributes to reducing the total stroke requirement.

The cold air ridedown test data does not represent a one hundred percent accurate quantitative representation of how the airbag will perform when inflated with a hot gas. Being less dense due to temperature, the gas will have a different effective orifice or valve coefficient. Compensation for this effect will be included in the final valve design. Experience with cold air testing of preliminary airbag designs assures that the tests conducted thus far do demonstrate the feasibility of the air bag vent valve concept whether used with either hot or cold gas.

The benefit of the vent valve in an OOPS may actually be many times greater than shown in the preliminary feasibility tests in Phase I. Smaller baseline vents, as now used in depowered airbags, would likely have shown even greater benefits. The total vent area in the Phase I baseline tests was nearer the high end of the vent area ranges for auto airbags, and the tests still demonstrated an obvious benefit. Also, the Talley D 60 inflator used in the Phase I tests is a new generation automotive airbag inflator. If the tests had been conducted with a more aggressive inflator of an earlier design, the OOPS tests would probably have shown a greater benefit associated with the prototype vent valves.

Furthermore, existing auto airbag vents may not even be exposed in some OOPS. The OOPS tests were conducted with two open 1.25-in. diameter ports. In typical automotive airbag modules, the vents are in the bag, not in the housing. Therefore, the bag must unfold before any gas flow can reach the vents. In a very close OOPS, the effective vent area may be essentially zero rather than the baseline vent area used in the tests. In such cases, the "as is" airbag configuration would be far more lethal in an OOPS than was indicated in the tests. Therefore, the data is indicative of valve performance, but more testing is required to demonstrate the total benefit of the system relative to typical automotive airbag systems.

Finally, the baseline condition plots are valid only for bags with exactly the same pre-charge. In an actual airbag application with orifice vents only, the pre-charge is not necessarily closely controlled. For example, temperature extremes greatly change the performance of hot gas inflators, and can therefore cause significant changes in the pre-charge.

Development to this point has made it apparent that the vent valve concept has applications other than the intended general aviation and automotive markets. For example, the US Army cockpit airbag system (CABS) for helicopters may benefit from inclusion of such a valve. These airbag systems are not vented like auto airbags are. The reason is that the typical crash scenario is much more protracted (ex: tree strikes prior to ground impact), and longer period of bag inflation is required. The unvented approach provides enhanced protection even with a hot gas generator, which fills the bag with hot gases that rapidly contract due to cooling. However, the design and production of the

inflator must be very precise to achieve the proper initial pressure. This is particularly difficult to achieve under the temperature extremes under which these helicopters operate. Inclusion of the NASA sponsored vent valve concept in the CABS system may be beneficial. Exactly the right pressure could be provided at bag inflation under all temperature conditions, and the pre-loaded valve would seal the bag (as desired) after inflation to the proper pressure. Inclusion of the valve would also greatly reduce rebound when the occupant did load the airbag. This rebound, quite energetic with a sealed bag, was initially shown to not present an unacceptable injury risk for the Army aviator population wearing protective equipment. However, elimination of this rebound may provide a highly desirable system enhancement.

CONCLUSIONS

The Phase I tests have demonstrated the feasibility of the basic concept for air bag vent control. In addition, the prototype valves designed and tested were shown to have many advantages over other valve configurations. An additional advantage of the vent valve is that it introduces a practical way to adjust valve performance for occupant size. The feasibility of this adjustment feature was demonstrated in the tests as well as the original objectives of reducing airbag size and weight and reducing lethality in an OOPS.

Specific conclusions are as follows:

- The response time of the vent valve design is fast enough for the intended function of regulating air bag exhaust flow. Tests at occupant/bag impact velocities of up to 22 ft/sec showed satisfactory performance. Component tests also showed that valve response time is negligible relative to system requirements.
- The vent valve can improve air bag efficiency as proposed.
- The valve may be easily adjusted to optimize performance for different occupant sizes.
- Some further development is required to achieve optimum adjustability over the entire range of performance conditions.

The OOPS tests showed that the vent valve design can also alleviate injuries associated with an OOPS. The tests showed that even the vent valves with the highest pre-load produced less peak pressure than did the baseline vent configuration. The tests with the vent valves also had significantly less pressure persistence time over 6 psi. Since injury criteria are highly dependent upon the duration as well as the peak value of contact forces, the second finding is especially significant.

The vent valve may have applications in other than the intended general aviation and automotive markets. The US Army cockpit airbag system (CABS) can probably benefit from inclusion of the vent valve. The valve would assure proper pressurization of the

unvented bag configuration under all temperature extremes, and would minimize undesired rebound. Airbag systems other than those used for occupant protection might also benefit from inclusion of such a valve. Planetary landing systems and aircraft escape capsules (such as previously used on the F-111) may be other potential applications.

ACKNOWLEDGEMENTS

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Prior work on airbag vent valves was conducted by the US Army Natick Research, Development, and Engineering Center (reference 3) and by Warrcik & Associates of Prescott, Arizona. The application involved aerial cargo delivery.

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Modeling Multi-Airbag Systems for Optimal Protection

Xavier J. R. Avula* and Ints Kaleps
Biodynamics and Acceleration Branch, Biodynamics and Protection Division
Human Effectiveness Directorate, Air Force Research Laboratory
Wright-Patterson Air Force Base, OH 45433-7947
(*NRC Senior Research Associate on leave from University of Missouri-Rolla)

ABSTRACT

Significant improvements have been made to increase the likelihood of crew survival during aircraft crashes including stronger aircraft structures, delethalization of the cockpit, and energy absorbing seats. Nonetheless, injuries and fatalities, due to head and upper body strikes with cockpit structures, are still occurring in crashes. To further improve safety, inflatable supplemental restraints similar to ones found to be effective in automobiles, are being designed and implemented in helicopters. However, aviation accidents produce impacts from various directions and these directions can change in time. To provide protection in these cases, multiple air bag systems are desirable. These must be properly sized and placed, have the appropriate material properties, and operate over the time period needed to provide protection to the crew member. In this study, both two- and three-airbag systems are modeled. The effects on the motion of a rigid sphere, representing the head of the occupant, are examined as a function of air bag geometry; placement of airbags; fabric density, thickness, elasticity, and surface friction; and internal pressure and temperature. These simulations provide a baseline for evaluating specific air bag system designs for their effectiveness in restraining the crew member and minimizing head accelerations.

INTRODUCTION

Innovative design concepts have made modern military aircraft crashworthy. Energy absorbing seat design and break-away components of the cockpit interior have resulted in fewer injuries due to impact accelerations. Despite significant advances in accident prevention, crashworthiness, and individual protective equipment, head and torso injuries due to flailing have continued to cause death and disability in survivable military helicopter accidents. A study of US helicopter crashes to quantify the impact parameters and identify hazards causing injuries and fatalities (Coltman et al., 1986) revealed that of one hundred and eighty six mishaps in a ten-year period (1972-1981), one hundred and fifty four were judged survivable. The use of supplemental inflatable restraint systems, which has been applied to reduce injuries in automobiles by minimizing occupant motion and subsequent collision with the vehicle's interior, has been extended to Army helicopters and its effectiveness demonstrated by the U.S. Army Aeromedical Research Laboratory (Alem et al.,1992). Alem et al. (1992) and Shanahan et al. (1993) have addressed the issue of airbags for aviation safety and concluded that an airbag system, specifically designed for a helicopter, could significantly reduce severe head and chest injuries and fatalities.

Multi-airbag systems, consisting of airbags deployable on the sides and ceiling, have recently been introduced in automobiles for better protection of occupants during lateral as well as frontal impacts. Strawn and Alem (1994) have extended the multi-airbag concept to Army helicopters and studied the pilot interaction with the airbags.

There has been an extensive use of finite element codes in the simulation of airbag deployment. The purpose of the simulations has been to predict occupant loads, acceleration levels, and other severity measures that can help identify the effectiveness provided by the airbag system.

In this study, a generic system of airbags that could be utilized in aircraft was simulated. The interaction of a rigid sphere, representing the head of a crew member, with multi-airbags is simulated to study the influence of factors such as number of airbags, airbag position, material properties, friction coefficient, and

linear and rotational velocities of the impactor, all of which can significantly influence the air bag system performance and effectiveness.

AIRBAG SIMULATION

The LS-DYNA3D - a general purpose, explicit finite element program - developed by Livermore Software Technology Corporation is used to simulate the interaction of a spherical impactor with an airbag system. The airbag model is described in Khalil et al. (1991). The model is based on an orthotropic elastic material model that can be used in conjunction with several shell elements. A simplified gas model based on the assumption of uniform thermodynamic properties (pressure, density temperature and internal energy) throughout the airbag is coupled to the airbag structure. The mathematical details of the finite element model and the implementation of the material model are adequately described in LS-INGRID Theoretical Manual (1994), and validation of the model in Avula et al. (1999). Using this validated model, the interaction of a single airbag and a system of airbags with a spherical impactor is investigated. A variety of simulations are generated which could be applied for different situations that arise in the use of inflatables in aviation.

A typical automotive driver-side airbag, with a diameter of 720mm, with two vent holes of 20mm diameter, and mass of 292 grams was used for the simulation. The numerical values for the material properties of the airbag fabric and the thermodynamic properties of the inflating medium were taken from Avula et al. (1999) and are given in Tables I and II, respectively.

Table I. Material Properties for Airbag Fabric

Parameter	Variable	Units	Values
Thickness	T	Mm	0.35
Density	ρ_{fabric}	Kg/m^3	1000
Young's Modulus	E	N/m^2	1.0x10^{08}
Poisson's Ratio	ν	Dimensionless	0.4

Table II. Thermodynamic Properties of the Inflating Medium and the Ambient Air

Gas	Parameter	Variable	Units	Value
Nitrogen	Specific Heat at Constant Volume	C_v	J/kg°K	741.0
	Specific Heat at Constant Pressure	C_p	J/kg°K	1038.0
	Temperature	T	°K	700.0
Air	Density	ρ_{air}	Kg/m^3	1.0
	Ambient Pressure	P_e	P_a	1.0x10^5

Several simulations that have potential aviation applications were performed:

(1) Deployment of an airbag from a small area in the base which could be a small portion of a tightly crowded instrument panel. With ever increasing need for space on the instrument panel, it is essential

to find as small a space as possible for airbag deployment. The airbag is then laterally impacted by a spherical object to observe the area covered by the deformed airbag obstructing the pilot's line of sight.

(2) Interaction of an inflating airbag and a spherical object moving with a constant linear and rotational velocity.

(3) Simulation to investigate the reaction force at the base and the consequent deformation of it with and without impact.

(4) The interaction of a spherical object moving with a constant velocity and two simultaneously deployed airbags with different friction coefficients. Initially, the sphere slips between the airbags, but with an increase in the friction coefficient it is found that the sphere can be stopped..

(5) A three-bag scenario was simulated and was found to be very effective in capturing the sphere. The effect of the distance between the side airbags on the containment of the spherical body was also investigated.

(6) To better understand net friction effects, the fabric density, elastic modulus, and surface friction coefficient of one of the two bags was varied and the effects on the impacting sphere were observed

RESULTS AND DISCUSSION

Deployment of an Airbag From a Small Area in the Base

The simulation of an airbag from a small, 2 in x 2 in square area in the base was performed. The inflation of an airbag and impact with a sphereical body is shown in Figure 1. This simulation demonstrates the feasibility of deploying an airbag from a small area and still having it effectively react with an impacting body. The impact with a sphere is displayed on the right

Impact of an Airbag With a Rigid Body With Linear and Rotational Velocity

Direct impact of an unfolding airbag and a rigid body with a linear velocity of 15 m/s and an angular velocity of 15 rad/s is sequentially displayed in Figure 2. In this simulation expanded contact of the airbag with the base and rotation of the sphere over the airbag is observed. This simulation allows the examination of glancing strikes to the airbags and the effects both on the striking body and the airbag.

Deformation of the Base Support During Inflation and Impact

In aircraft, the instrument panel serves as the base for mounting the airbag module. The deployment of the airbag and subsequent impact exert a dynamic force on the panel which should be designed to withstand it. The simulations shown in Figure 3 indicate the deformation of the base support during inflation with and without impact by the spherical body. Simulations indicate a large deflection complemented by a greater curvature of the base plate during impact by the sphere. Large deflections correspondingly introduce large stresses that need to be considered in the design and material selection for the base plate.

Interaction of Dual Airbags With a Rigid Sphere

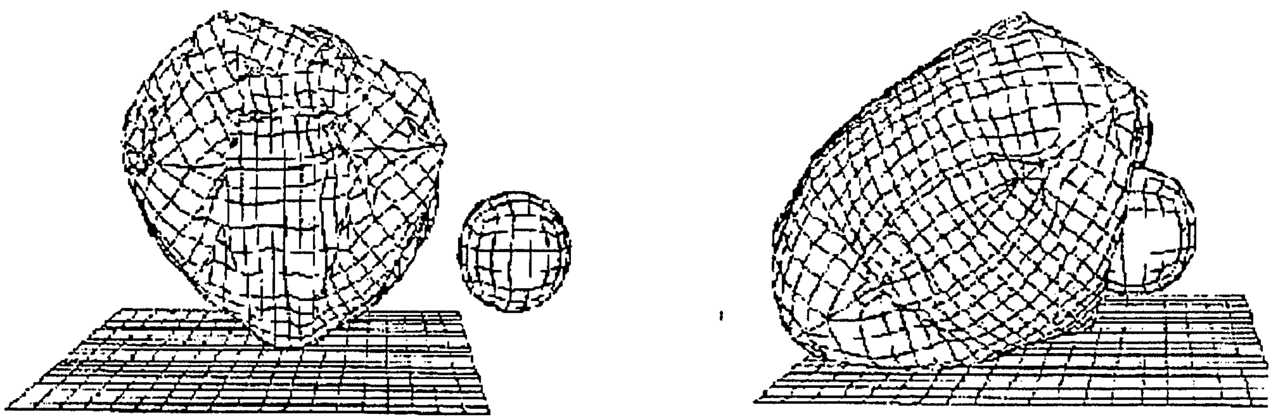
Consider the scenario consisting of two airbags and a rigid sphere as shown in Figure 4-a. The sphere, travelling with a velocity of 10 m/s is initially at a distance of 500 mm from the base support when the airbags are simultaneously triggered to deploy. Choosing the coefficient of kinetic friction $\mu = 0.1$, the motion of the sphere is observed. It is clear from Figure 4-b that the sphere begins to emerge from the grip of the airbag pair. Figure 4-c shows that the sphere slips through the fully inflated pair of airbags as indicated by its complete detachment from the grip of the airbags. Assuming that the sphere represents the head of an occupant, the two bag scenario, with low friction, does not provide sufficient resistance to motion to restrain the head during the crash.

By increasing the coefficient of kinetic friction to $\mu = 0.3$ the sphere is completely arrested by the airbag pair as shown in Figure 4-d. This action is attributed to increased friction since all the other parameters were held constant. Further increase in friction to $\mu = 0.4$ also results in the arrest of the moving sphere, but

much earlier than in the previous case, as shown in Figure 4-e., indicating that friction can be an effective mechanism for restraining body motion.

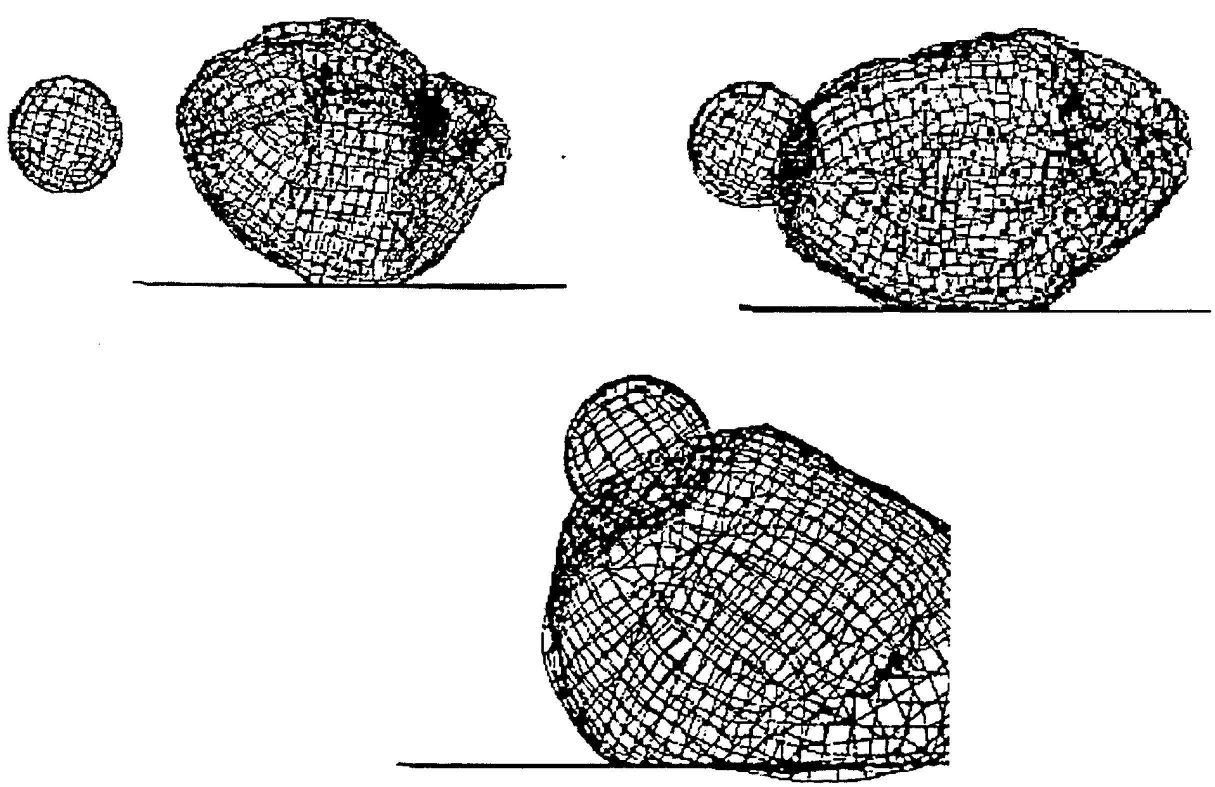
Interaction of Three Airbags With a Rigid Sphere

To further reduce the possibility of slipping past the airbags, a three airbag configuration was considered where two airbags were placed at the sides of the occupant and the third in the front as shown in Figure 5 a. Using the same specifications for the sphere, airbags, and the initial positioning, the sphere moving with a velocity of 10 m/s and zero-angle of inclination and friction coefficient $\mu = 0.1$ is allowed to strike the inflating three-airbag system. The airbag configurations for this case after inflation are shown in Figure 5



b. The protection offered by

Figure 1. Deployment of an airbag from a small area and impact with a sphere.



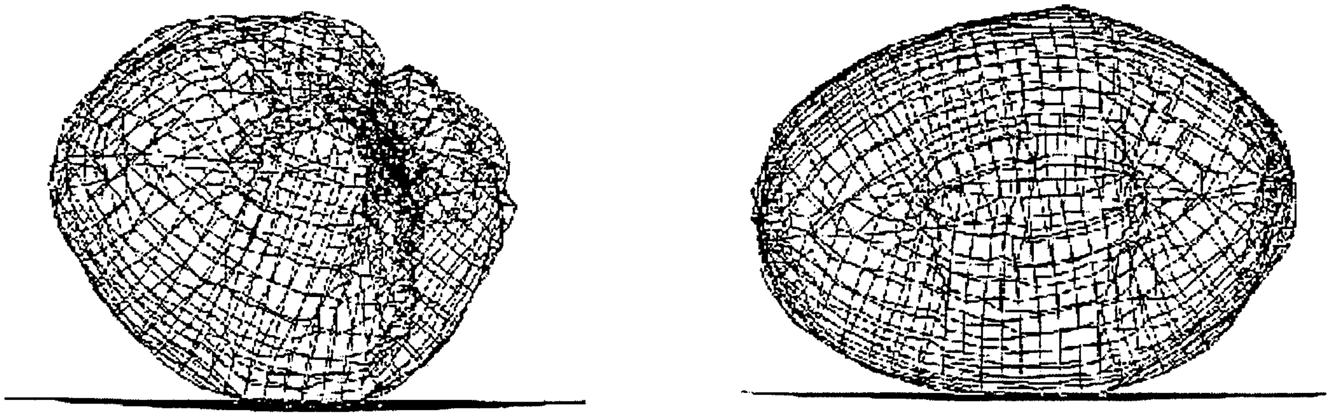


Figure 2. Sequential display of the airbag-sphere interaction with direct rotational impact.
Linear velocity = 15 m/s and angular velocity = 15 rad/s

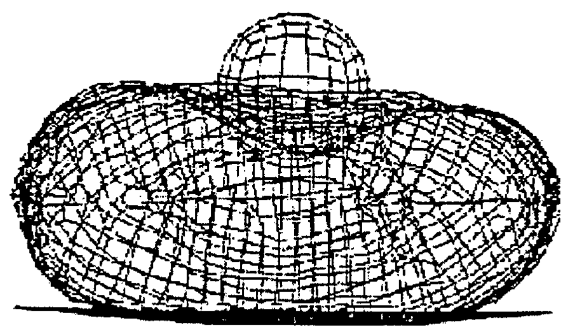


Figure 3. Sequential display of the deformations of the base support during inflation and impact

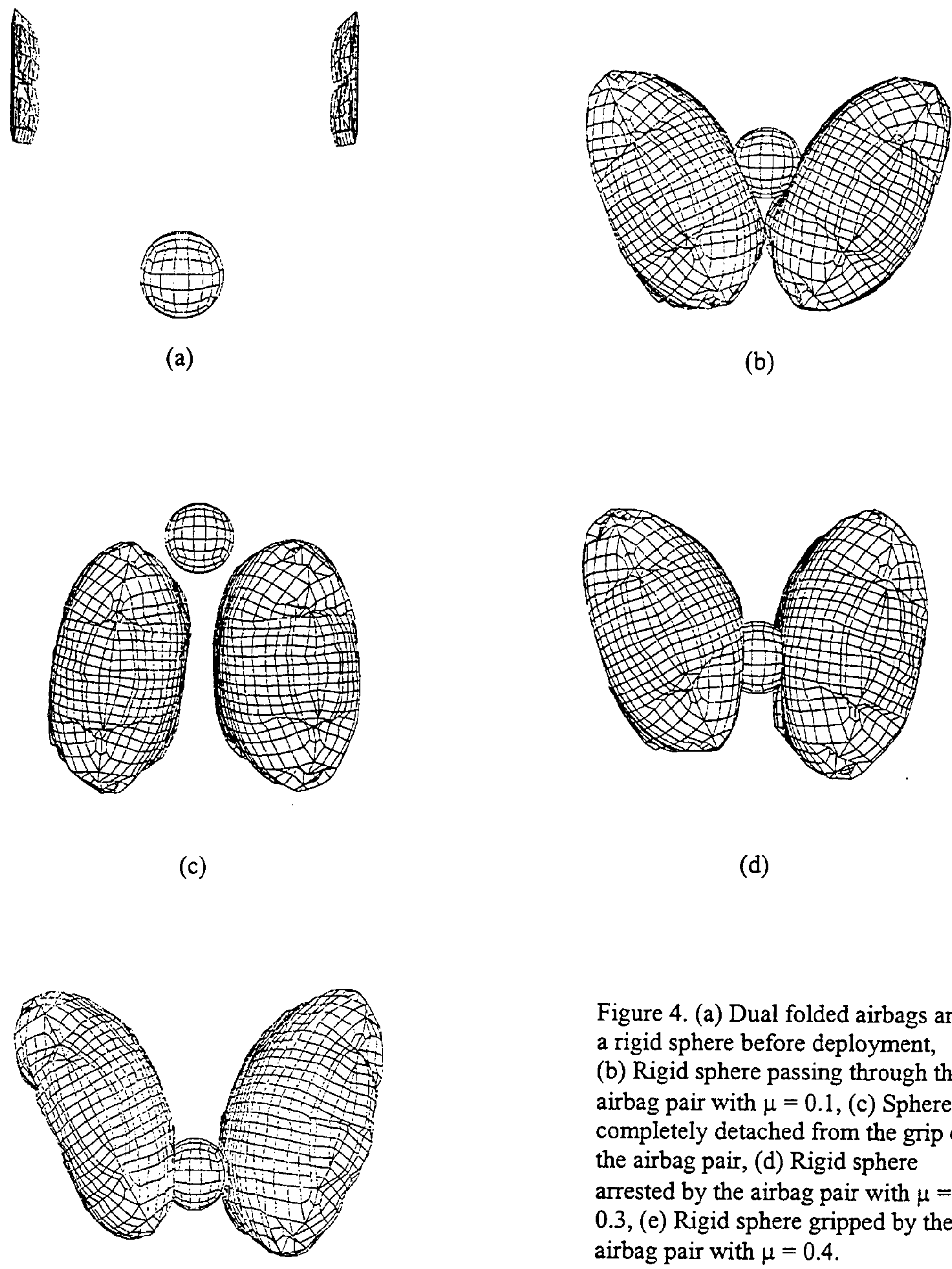
this type of system is definitely superior to the two-bag system as indicated by the total containment of the sphere within the boundaries of the three-airbag system. Without the frontal airbag, the sphere would have slipped through as shown in the above section. If the distance between the side airbags is relatively large, flailing can occur as depicted in Figure 5-c due to the space available for the rigid body to move around.

The evolution of pressure and gas temperature in all the three bags are shown in Figures 5-d,e. No significant differences in pressure and temperature are observed in these airbags during the impact phenomena.

Deployment of a Dual Airbag System Having Different Thickness and Elastic Modulus

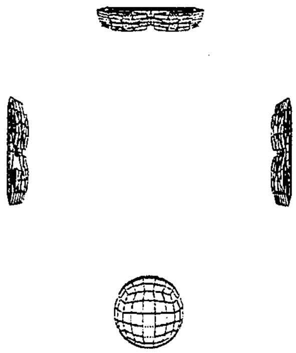
In this section, we simulate the dual airbag system with a value of the friction coefficient ($\mu = 0.4$) that we know is sufficient to stop a sphere from passing through. Holding all the other properties of the airbags as previously stated in Table I, the wall thickness and elastic modulus of the right hand side airbag were changed as follows: thickness = 0.20 mm and elastic modulus = $1.0\text{x}10^{07}$ N/m.

The airbag configurations are shown in Figures 6-a,b,c. Because of the differences in material properties, the dual airbag system produced an asymmetric response as depicted in Figure 6-a. Although we have used the same friction coefficient that has stopped the sphere earlier, now the sphere passes through because the



(a) (b) (c) (d) (e)

Figure 4. (a) Dual folded airbags and a rigid sphere before deployment, (b) Rigid sphere passing through the airbag pair with $\mu = 0.1$, (c) Sphere completely detached from the grip of the airbag pair, (d) Rigid sphere arrested by the airbag pair with $\mu = 0.3$, (e) Rigid sphere gripped by the airbag pair with $\mu = 0.4$.



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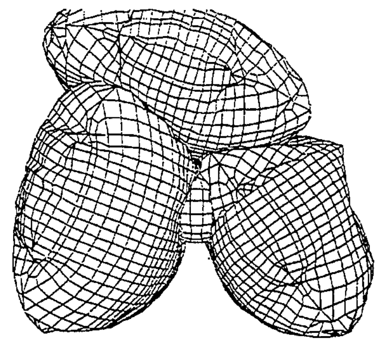

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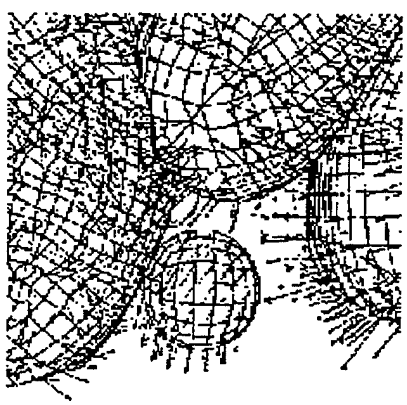

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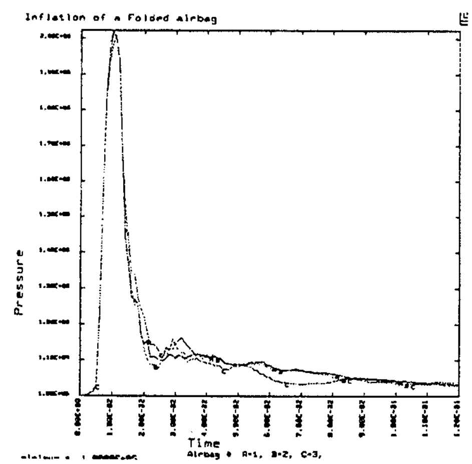

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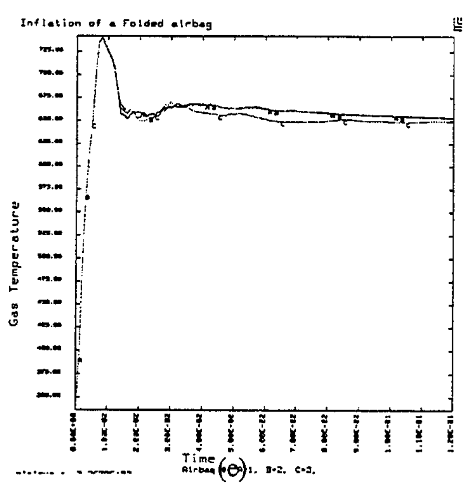
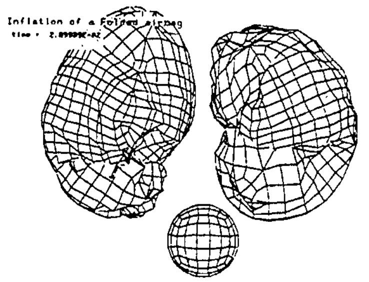


(e)

Figure 5. (a) There folded airbags and a rigid sphere before deployment, (b) Containment of the rigid sphere at full inflation of the airbags; $\mu = 0.1$, (c) Flailing motion of the sphere in the available space between the inflated airbags, (d) Evolution of pressure in the airbags. No significant differences are observed in the pressure profiles, (e) Evolution of gas temperature in the airbags. No significant differences are observed in the temperature profiles.



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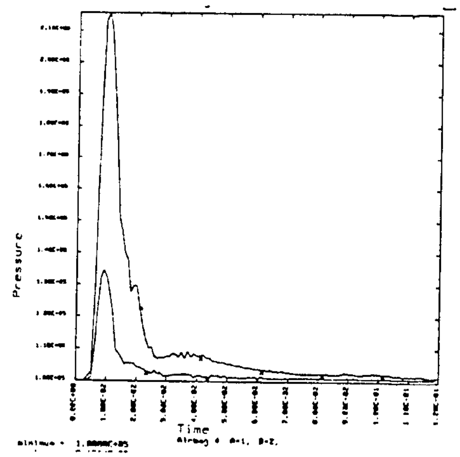

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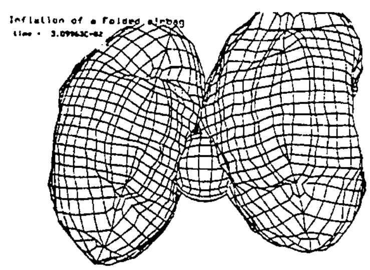

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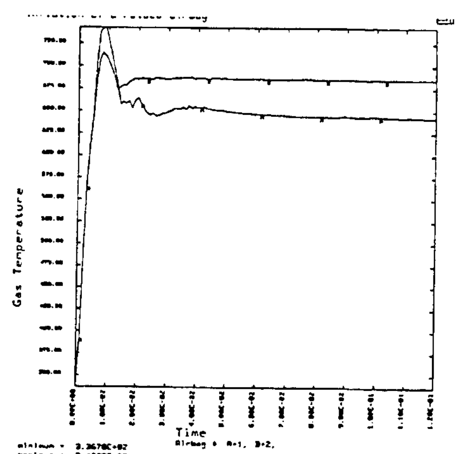

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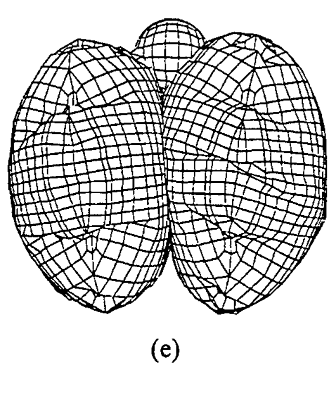

(e)

Figure 6. (a) Rigid sphere before impact with airbag pair of different material properties ($\mu = 0.4$), (b) Contact between the sphere and dual airbags with different material properties, (c) Emergence of the sphere from the rear of the airbags indicating slipping, (d) Evolution of pressure in the dual airbag system with different material properties, (e) Evolution of gas temperature in the dual airbag system with different material properties.

airbag expands rather rapidly in obeyance of the universal gas law, the bag attains higher temperature and lower pressure. Lower pressure in the bag means lower resistance offered to the impactor. Hence the impactor passes through the airbags.

CONCLUSIONS

A number of simulations that represent aviation airbag implementation conditions were performed. These are not specific for any one airframe or design specification, but should be viewed as baseline simulations that can be used for concept exploration, parameter trade-off studies, and better insights for airbag system design.

Since cockpit space is at a premium, deployment from a small 2in x 2in square aperture was performed. This simulation shows that an airbag tethered over a small area can effectively re-act impact forces.

The effects of body rotational motion were considered. Impact of an airbag by a body having an initial rotational velocity tends to deflect the body over the airbag leading to possible strikes with other parts of the aircraft structure. As the extent of this motion depends upon the air bag properties, appropriate caution must be exercised in the design of the airbag system.

During inflation and impact of the body with the airbag, the instrument panel must re-act significant forces. This issue should be addressed in the design for strength and durability of the instrument panel and other airbag supporting structures.

Variations in airbag surface friction, elasticity, and fabric density were explored and found to produce highly interactive effects. It was demonstrated that friction can have an effect on restraining motion, but that changes in airbag elasticity and density can have off-setting effects. A decrease in elasticity makes the bag more flexible, leading to lower normal forces and thus less friction on an incident body. Increased fabric density produces greater initial normal forces and hence increases friction forces at first contact. While each of these parameters has a direct effect on system response, it is important to keep in mind that changes in other parameters can significantly modify that response.

In a potential multi-directional impact environment multiple airbags are essential. While it may be intuitively obvious that more airbags than less are desirable, it is imperative that they work in concert to provide the appropriate restraint at the right time. The simulations in this study demonstrated single, double, and triple airbag systems, and their interactions with each other as well as with a rigid impacting body.

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Design of Inflatable Restraints for Crew Using Madymo

William Rockwell
TNO-MADYMO North America
Tel: (248) 449-1755
Fax: (248) 449-7574
E-mail: sales@madymo.com

The application of inflatable restraints in aviation is becoming more common. An example of where this implementation is starting to take place is in small aircraft crew seat modeling. Using the software MADYMO, a study has been done on a crewseat to see the benefits of integrating an inflatable restraint during a standard crash impulse. Before going into the details and results of this model, a background on MADYMO will be explained.

MADYMO BACKGROUND

MADYMO is a software package that allows users to design and optimize occupant safety systems efficiently, quickly and cost-effectively. The name is derived from MAthematical DYnamic Model. It is a worldwide standard for occupant safety analysis and simulation. It is used extensively in industrial engineering departments, design offices, research laboratories and technical universities. It has proven itself in numerous applications, often supported by verification studies using experimental test data.

Using MADYMO, an occupant safety system can be thoroughly assessed and easily optimized early in its development cycle. This is useful in avoiding the delays and costs involved in having to change a product late in its development. MADYMO also reduces the need for costly and time-consuming mechanical prototypes. As a result, production processes are drastically streamlined, and users can get their products to market more quickly.

MADYMO SOLVER

The MADYMO solver uses both Multibody and Finite Element techniques together. It also provides specialized options such as advanced seat belt systems, and many thermodynamic options for modeling airbags. It's multibody capabilities stem from its mathematical foundation and the occupant models developed by TNO. Multibody systems can be simply described as rigid and flexible bodies (or masses) that are interconnected by various types of kinematic joints. This quick, computationally efficient method of modeling dynamic systems and in particular, occupant kinematics is ideal for performing large parametric design studies. For this reason, TNO has developed an extensive library of occupant models, principally using Multibody techniques.

To effectively model contact interaction, geometry can be assigned to bodies, allowing their surface definition to be accurately defined. Besides standard joints such as revolute, universal, spherical, cylindrical, translational, and planar joints, users can create customized kinematic joints. Joint properties such as elasticity damping and friction between bodies can be easily defined. Also, the locking and unlocking of joints allows the simulation of breaking bodies according to user-specified conditions.

To effectively model restraint system components and airbag systems, as well as deformable structures and surfaces, MADYMO offers Finite Element capabilities. These are ideal for capturing large deformations of nonlinear materials, and for modeling deformable contact. Madymo's explicit transient finite element solver includes an extensive choice of efficient brick, shell, membrane, beam, and truss elements. Many material models are available, including metals, rubbers, fabrics, and foams. Contact interactions between finite elements and multibody surfaces can be specified. Many numerical techniques are available to increase the overall efficiency of the finite element method.

MADYMO DUMMY DATABASES

MADYMO has a high quality range of recognized crash dummy models, all highly realistic and validated. Most dummy models are created using the computationally efficient multibody technique, however, many finite element occupants are also available. MADYMO also offers a new generation of simulated crash dummies, generated by "hybrid" modeling techniques. Hybrid modeling is used for different design phases. Multibody techniques are used for fast prototype development and Finite Element techniques for more detailed modeling of structural components. The great advantage of MADYMO is that all these techniques can be blended to create the most efficient model for a specific situation.

MADYMO IN AVIATION

By analyzing customized MADYMO models, users can study occupant behavior during aircraft crashes. Results from these studies can help to design safer aircraft seats and significantly reduce product development time. It has also been used to evaluate and optimize restraint systems. With MADYMO, users can meet various standards for crash dummy type, barrier type, injury criteria, etc.

The crew seat model was constructed using both multibody and FEM features. The model consists of a FEM seat and FEM glareshield. This permits a more detailed analysis of these components as the occupant comes into contact with them. A combination of shell and solid elements are used depending upon their interaction with the model.

The occupant system is modeled with a 50-percentile Hybrid II dummy. This model is commonly used when studying occupant dynamics in the aviation industry. The occupant is restrained using a mixed FEM and MADYMO 4-point seatbelt system. The FEM component is used to model the belt straps as shell elements and considers their contact with the occupants waist and chest. The MADYMO components of the belt attach at the ends of the FEM belts. MADYMO segments are used because they effectively model the slip rings, retractors and pretensioners.

To capture the deflections and preloading of the FEM seat, an initial run was used to model the dummy settling into the seat due to gravity. Once the dummy had settled into position, the coordinates were recorded. These coordinates were then used to place the dummy into the seat during the simulation before the crash pulse is applied. Once the dummy was placed, a 16g pulse was applied over a 180 milliseconds duration.

The baseline model was set-up without an inflatable restraint. It showed that the occupant came into contact with the glareshield. The loading on the head and chest indicated forces that were life threatening based on HIC and 3MS references. The 4-point restraint system and FEM seat did absorb a significant quantity of energy in the run. Preliminary modeling indicates that these systems could be modified to improve their effectiveness. This study, however, concentrated on the benefits of the application of an inflatable restraint.

The second model integrated an inflatable restraint into the glareshield. This restraint was triggered 20 milliseconds into the crash pulse. The results of this analysis indicate that the peak head and chest forces were significantly lower than the baseline model. It should be noted that the head and chest did take increased loading during the initial contact with the inflatable restraint, however, the peak values decreased. It is this exchange (higher preliminary loading and less peak loading) that makes the argument of an inflatable restraint a benefit.

The small aircraft crewseat model with an inflatable restraint is still being investigated. This preliminary study presents the advantages of using a tool such as MADYMO to determine the effectiveness of such a system.

Evaluation of Upper Extremity Injuries From Lateral Air Bag Deployment

Stefan Duma, Brian Boggess, and Jeff Crandall
Automobile Safety Laboratory, University of Virginia, 1011 Linden Avenue, Charlottesville, VA, 22902*

ABSTRACT

A review of upper extremity injury criteria is presented for determining the injury potential of a deploying lateral air bag. Experimental studies that range from the late 1800's to the late 1900's are summarized. In order to determine conservative injury criteria, it is suggested that the criteria be established from those studies that utilized female upper extremities. Also, more accurate criteria can be determined by utilizing data from dynamic experiments with loading rates similar to those observed under air bag loading. Given these restrictions, four injury criteria for the 5^{th} percentile female upper extremity are established: humerus fracture criterion of 128 Nm, forearm fracture criterion of 58 Nm, and chondral and osteochondral fractures of the elbow joint criterion of 314 g's measured at the distal radius or 51 Nm measured at the distal humerus. Injury risk functions are also presented for each region. Until future research is conducted, the injury criteria developed from cadaver tests should be used directly with the 5^{th} percentile female dummy upper extremity in order to provide an initial assessment of injury risk.

INTRODUCTION

The purpose of this study is to review the literature and present the most applicable upper extremity injury criteria for the evaluation of lateral air bag loading. Due to their smaller stature and bone structure, and post-menopausal bone mineral loss, women are considered to represent the most vulnerable occupants to out-of-position air bag loading (Motoshima, 1960 and Duma, 1998a). Therefore, this study presents the injury criteria for the small female as the most conservative case for occupants exposed to air bags. An anatomy review is presented followed by a discussion of the humerus, forearm, and elbow injury criteria research.

ANATOMY

The upper extremity is composed of six morphologically distinct regions: the shoulder, upper arm, elbow, lower arm or forearm, wrist, and hand (Figure 1). This paper focuses on the shoulder, upper arm and elbow regions. The shoulder joint, which is formed by the clavicle, scapula and humerus, is the most mobile joint in the human body (Kapandji, 1982). The movement of the clavicle and scapula allows translation of the shoulder in the horizontal and frontal planes. Rotations about the three anatomical axes are provided by the shoulder joint and are referenced to the neutral position which has the humerus oriented vertically with the distal end down. The distal head of the humerus and the proximal ends of the radius and ulna comprise the elbow joint (Figure 2). A much simpler joint than the shoulder joint, the elbow allows flexion of the forearm toward the humerus, extension of the forearm away from the humerus, and one half of the forearm pronation/supination rotations. Closer examination of the elbow joint reveals that flexion/extension is guided by the trochlea of the humerus, in which the trochlear notch of the ulna travels.

The pronation and supination movements of the forearm are allowed through two rotations. First, the proximal radius head rotates on the capitulum of the distal humerus to allow for the elbow contribution. Second, these rotations are completed by the ulna rotating at the wrist. Additionally, the proximal and distal radio-ulnar joints allow the radius and ulna to rotate with respect to each other. In the supinated position, the radius and ulna are essentially parallel to each other, whereas in the pronated position, the distal radius rotates over the ulna and brings the radius across the ulna (Figure 3).

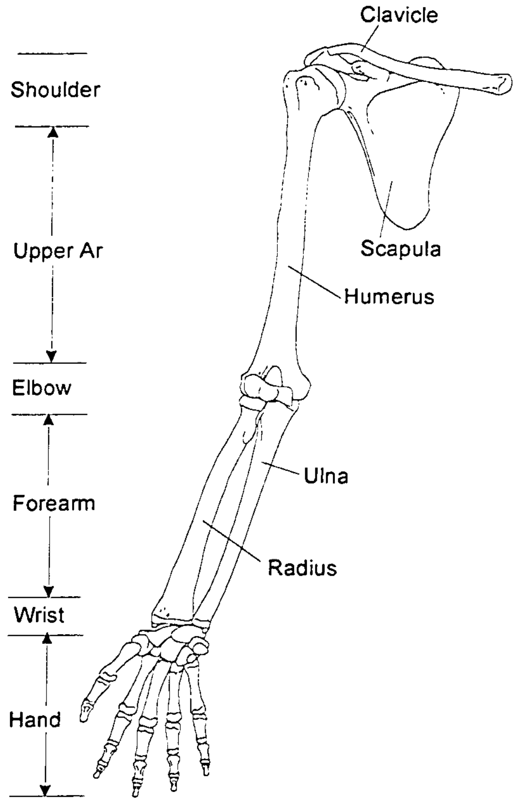

Figure 1. Anatomy of the upper extremity.

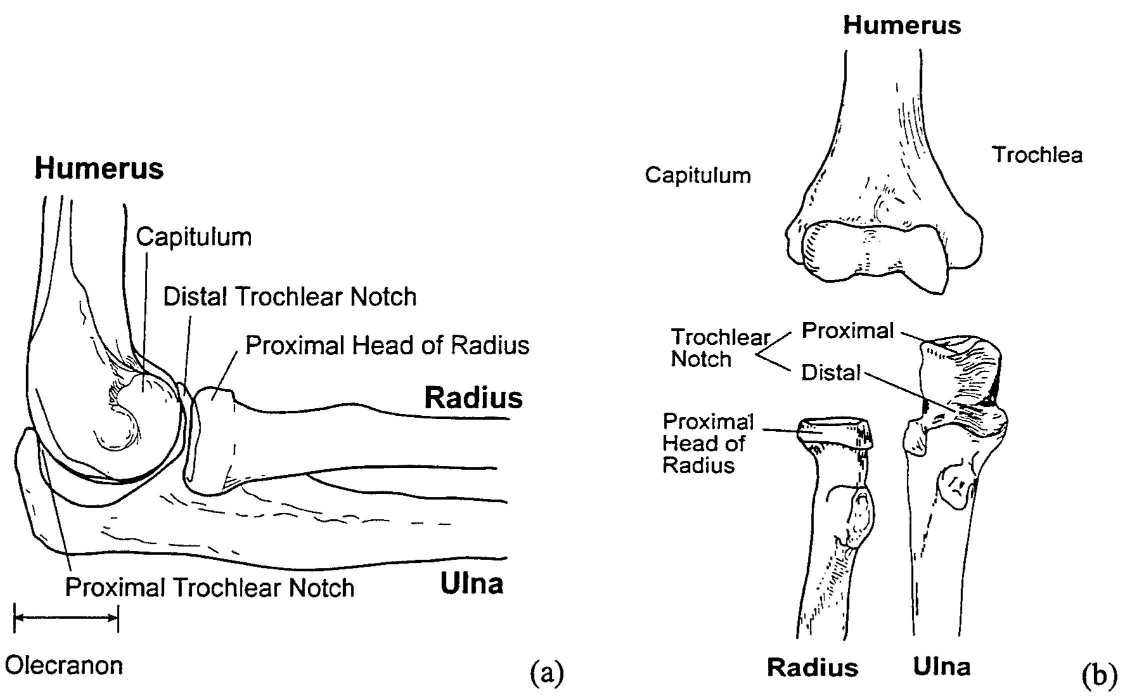

Figure 2. Anatomy of the elbow joint, lateral view (a), anterior view (b).

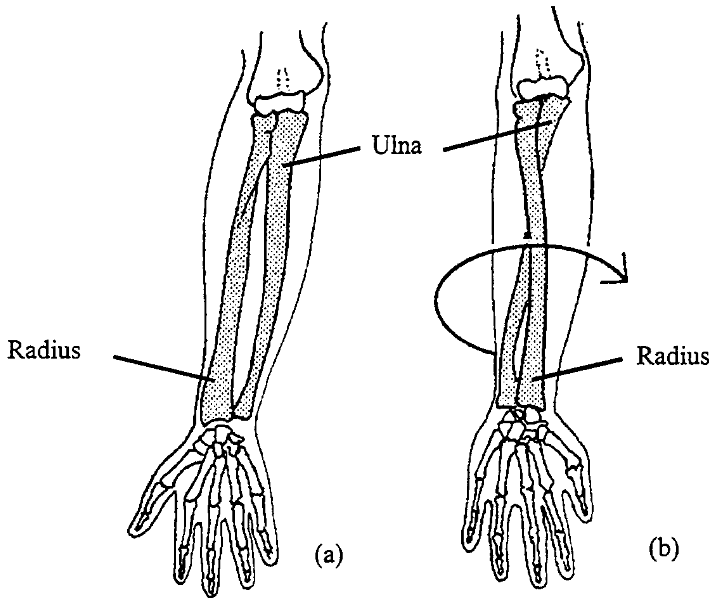

Figure 3. Position of the radius and ulna with the forearm fully supinated (a) and fully pronated (b).

HUMERUS INJURY CRITERIA

Several studies are presented in the literature that utilized cadaveric humeri under 3-point bending to investigate the ultimate bending strength (Table 1). The male and female humerus bending failure was investigated by Weber (1859) and Messerer (1880), but these studies are dated and involve sample populations that are likely different than the modern population. The values presented by Motoshima (1960) should underestimate the bending tolerance given the anatomical and nutritional differences between the study's test subjects and the current population. The study by Kallieris *et al.* (1997) is limited in that only three male humeri were used. Kirkish *et al.* (1996) tested only one female, but did demonstrate with additional male humeri that bending failure in the anterior/posterior direction was not significantly different than in the lateral direction. This was attributed to the near-cylindrical geometry of the mid-shaft humerus. The independence on loading direction suggests that a single humerus injury criterion could be used to evaluate the risk of injury from a lateral or posterior loading.

Table 1. Humerus fracture tolerance studies from quasistatic 3-point bend tests; standard deviation in parenthesis.

		Male	**Female**
Study	**Year**	**Bending Failure (Nm)**	**Bending Failure (Nm)**
Weber	1859	115	73
Messerer	1880	151	85
Motoshima	1960	104 (± 8)	84 (± 5)
Kirkish	1996	155 (± 45)	84
Kallieris	1997	138 (± 9)	--

The most relevant humerus tolerance was established by Duma et al. (1998a). This study utilized only female limbs in a dynamic test environment. Twelve female humeri were prepared by disarticulating the upper extremity at the shoulder and elbow joints. The average age of these specimens was 57 ± 11 years with an average body mass of 58.7 ± 7.6 kg. Enough soft tissue was removed from each humerus to expose 50 mm of bone at the distal and proximal ends. The exposed ends were potted in PC-7 epoxy putty to a depth of 30 mm using removable molds. Simple support fixtures were attached to the hardened epoxy. Strain gages (Micro Measurements, model CAE-13-

125UN-350) were adhered mid-shaft on both the anterior and posterior sides of the humerus to provided maximum tensile and compressive strains. Pre-test CT scans of each humerus were taken (5 mm contiguous slices) to determine bone cross-sectional properties. Dynamic three-point bending tests were performed using a 9.48 kg impactor released from a drop height of 1.35 m. The impactor was guided by a vertical linear bearing track which resulted in a pre-impact velocity of 3.63 m/s. This velocity was chosen to match humerus strain rates as measured in cadaveric subjects under side air bag loading. The humerus was impacted mid-shaft in the posterior-anterior direction. This direction was chosen to correspond with the direction of humerus loading that would be seen from a deploying seat mounted side air bag. The average moment to failure when mass scaled for the 5^{th}% female was 128 ± 19 Nm. By assuming a normal population distribution, an injury risk function for humerus fracture may be generated by integrating the normal curve with an average value of 128 Nm and standard deviation of 19 Nm (Figure 4). This technique for generating injury risk functions should be used only if the logistic regression method cannot be employed. For these tests, there are no known injury experiments with which to utilize the logistic regression technique.

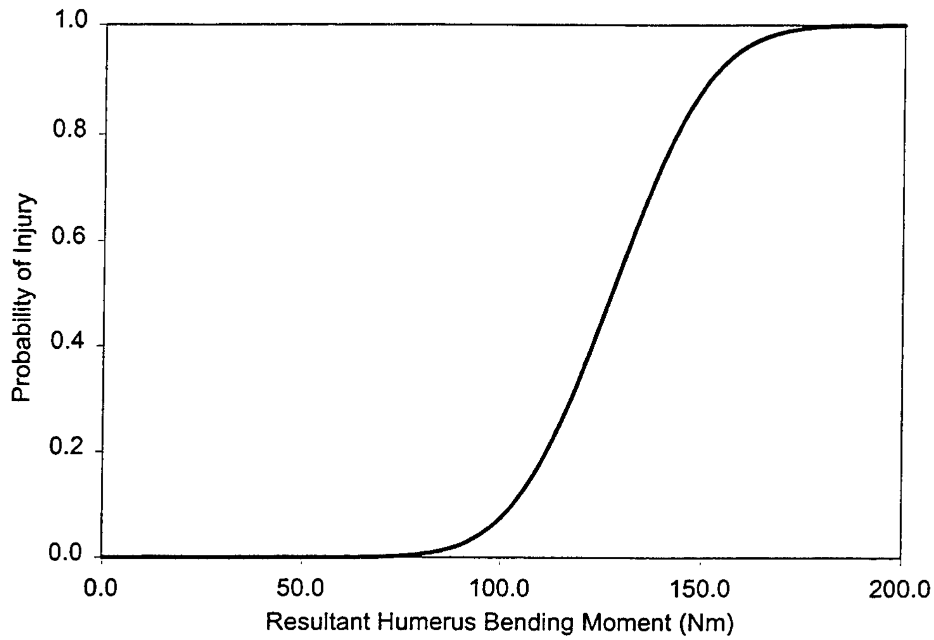

Figure 4. Humerus bending moment injury risk function for the 5^{th}% female.

FOREARM INJURY CRITERIA

The forearm fracture tolerance has been investigated by fracturing the radius and ulna separately, as well as concurrently. All studies that have examined the radius and ulna separately, have been performed under quasistatic loading conditions in 3-point or 4-point bending (Table 2). Unfortunately, the studies by Yamada (1970), Jurist (1977), and Swanson (1990) do not report results divided by male and female populations. This resulted in large standard deviations for the Jurist (1977) and Swanson (1990) studies.

Deriving an average radius and ulna failure moment from the existing data is difficult considering that the tests span over a hundred years with three different national subject populations. In addition, there are considerable differences in the test protocol among the six studies. Weber (1859), Messerer (1880), and Yamada (1970) tested fresh specimens, while the remaining three studies utilized embalmed bones. Also, the direction of loading is not consistent between studies. This is a result of the orientation of the bones in full pronation versus full supination. Given these caveats on the use of this data, the average ulna ultimate bending strength for the female and unknown group for all the quasistatic studies is 39 ± 6 Nm, and the average radius ultimate bending strength is 35 ± 5 Nm. These averages are taken by weighting each study result by the number of subjects in the study.

Table 2. Quasistatic bending tolerance studies; standard deviation in parenthesis.

Study	Protocol	Subjects	Female		Male		Unknown Gender	
			Radius (Nm)	Ulna (Nm)	Radius (Nm)	Ulna (Nm)	Radius (Nm)	Ulna (Nm)
Weber (1859)	3-point bending	5F	--	35	--	--	--	--
Messerer (1880)	3-point bending	6F, 6M	23	28	48	49	--	--
Yamada (1970)	3-point bending	35	--	--	--	--	37	45
Jurist (1977)	3-point bending	45	--	--	--	--	--	38 (15)
Swanson (1990)	4-point bending	10	--	--	--	--	31 (16)	--
Bass (1997)	4-point bending	4F	40	36	--	--	--	--

In order to use the quasistatic single bone failure data for the development of the forearm failure criterion, Saul et al. (1996) proposed a simple method of directly combining the individual criteria, and then multiplying by 1.5 to account for dynamic loading. This means that he added 39 Nm for the ulna with 35 Nm for the radius, and then multiplied bye 1.5 to get an injury criterion of 111 Nm for the small female. While this method does provide an initial estimate, there are two important factors ignored with this reasoning that make the injury criteria of 111 Nm useless in automobile safety research. First, it does not account for the direction of loading and the initial position of the forearm. Second, the role of the interosseous ligament, which is a strong ligament that connects the radius and ulna in the mid-forearm, is not accounted for. It has been shown that the interosseous ligament can account for a 20 % load transfer from one bone to the other (Pfaeffle, 1999).

Two recent studies have tested intact cadaveric forearms. This first by Pintar et al. (1998) performed dynamic 3-point drop tests on 12 female cadaver forearm specimens. He found the mean failure bending moment of 66 ± 25 Nm; however, he only performed tests in the supinated position. Thus, it is difficult to apply his data, given that a typical driver's upper extremity is positioned in front of the air bag between a neutral and fully pronated position. The most recent study presented by Begeman et al. (1999) tested 10 male forearms in the lateral direction and developed a bending tolerance of 89 Nm. This study is limited in that only male forearms were used, and no tests were performed in which both the radius and ulna failed.

The most useful forearm tolerance was established by Duma et al. (1998a). This study utilized only female limbs in a dynamic test environment and examined the effect of pronation and supination on the ultimate bending strength of the forearm. Ten female forearms were prepared by disarticulating the upper extremity at the shoulder and keeping the elbow joint intact. The average age of these specimens was 61 ± 5 years with an average body mass of 59.1 ± 11.6 kg. Simple mounts were designed to attach to the posterior side of the forearm via two tie wraps. This mounting technique allowed for the forearm to be oriented in the supinated or pronated position prior to testing. The three-point drop test device used for the humerus tests was again employed with the drop height adjusted to 2.0 m resulting in an impact velocity of 4.42 m/s. This velocity was chosen to match radius and ulna strain rates as measured in cadaveric tests with driver side air bags (Bass, 1997). In both the pronated and supinated positions, the upper extremity was positioned such that the impactor struck the anterior surface of the forearm. The impact location was established as the distal third of the forearm, which was taken as two-thirds of the ulna length measured distally from the olecranon. This location was chosen due to the local minimum polar moment of inertia of both the ulna and radius at the distal third of the forearm (Bass, 1997).

Using three matched forearm pairs, it was determined that the forearm is 21 % stronger in the supinated position, 92 ± 5 Nm, versus the pronated position, 75 ± 7 Nm. Two distinct fracture patterns were observed for the pronated and supinated groups. To produce a conservative injury criterion, a total of 7 female forearms were tested in the pronated position. This resulted in the forearm injury criterion of 58 ± 12 Nm when scaled for the 5^{th}% female. By

assuming a normal population distribution, an injury risk function for forearm fracture may be generated by integrating the normal curve with an average value of 58 Nm and standard deviation of 12 Nm (Figure 5).

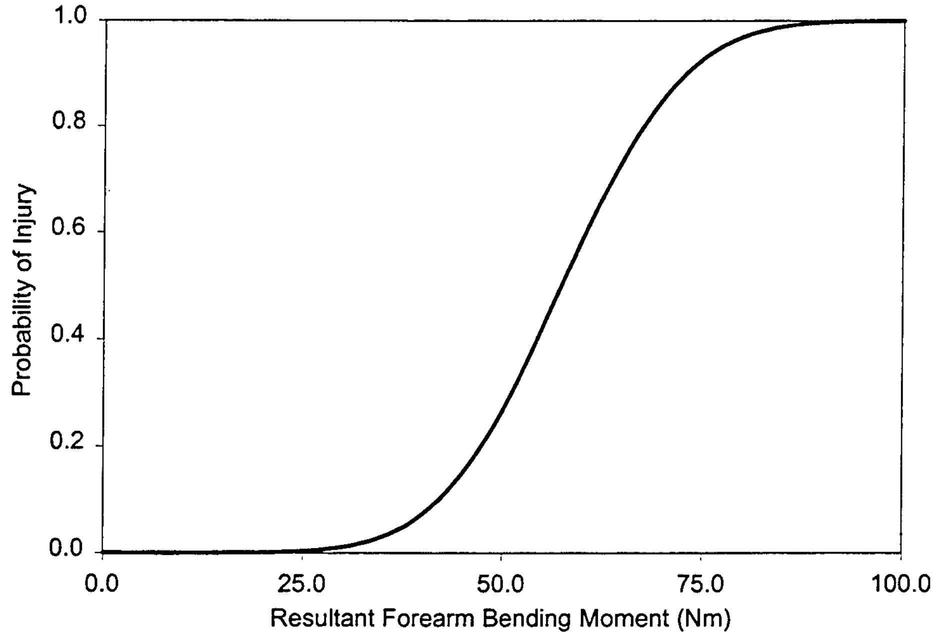

Figure 5. Forearm bending moment injury risk function for the 5^{th}% female.

ELBOW INJURY CRITERIA

The interaction of the small female upper extremity and a deploying side air bag was characterized by Duma et al. (1998b) using dummy and cadaveric test subjects. The humerus was loaded by three types of seat-mounted side air bags. Chondral and osteochondral fractures were observed in seven of the twelve cadaver tests, while a simple fracture of the distal humerus head was observed in one test. The chondral and osteochondral fractures were all found within the elbow joint (Figure 6). Compression and extension injury mechanisms were suggested for the observed elbow injuries, and injury risk functions were generated using logistic regression; however, more research is needed to elucidate the exact failure criterion of the elbow.

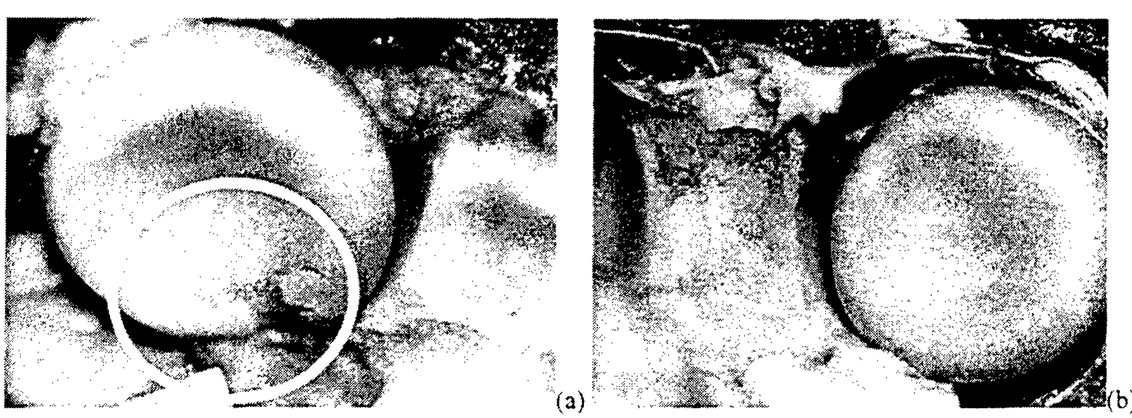

Figure 6. Chondral fracture of the proximal radius head (a) from side air bag loading of the humerus versus the uninjured proximal radius head (b).

Statistical analysis was conducted to develop injury criteria based on measured physical parameters. Linear logistic regression analysis was used to associate cadaver injuries to dummy and cadaver measured test parameters. The first analysis compared all recorded injuries to all peak signals in the cadaver tests and the corresponding dummy tests. The most significant correlation was observed between the presence of injuries and cadaver age ($p = 0.01$). The second most significant correlation was between the presence of injury and the dummy resultant forearm acceleration ($p = 0.05$), which showed a 50% risk of injury at 270 g's.

The chondral and osteochondral fractures in the elbow joint were separated into two categories corresponding with two proposed injury mechanisms. A second linear logistic regression analysis was performed to investigate the direct contact injury mechanism. This analysis included all distal trochlear notch and proximal radius head injuries. The injuries were correlated to peak signals in the cadaver tests and corresponding dummy tests. Again, the cadaver age was the most significant factor ($p = 0.002$). There was complete injury separation at 54 years with the older three subjects recording injuries in this category and the younger two recording no such injuries. A weaker correlation was found with the dummy distal humerus moment MY ($p = 0.07$). The injury risk curve for this sensor gave a 50% risk of injury at an elbow moment of 51 Nm (Figure 7).

While the severity of a forearm or humerus fracture is well understood, the pathology of the articular cartilage injuries, such as those observed by Duma et al. (1998b), is less understood. This study noted that the first obstacle is that chondral and osteochondral fractures may not present on a radiograph of the elbow, given the overlap of the trochlea and trochlear notch. Even if detected, they can be very difficult to treat. The damaged cartilage does not heal well without surgical intervention due to the lack of vascularity and the relative low metabolic activity of the chondrocytes, or cartilage cells (Sue, 1995). The prognosis for chondral and osteochondral fractures in the elbow is an arthritic joint that will most likely not heal. While these are not life-threatening injuries, they can be very painful.

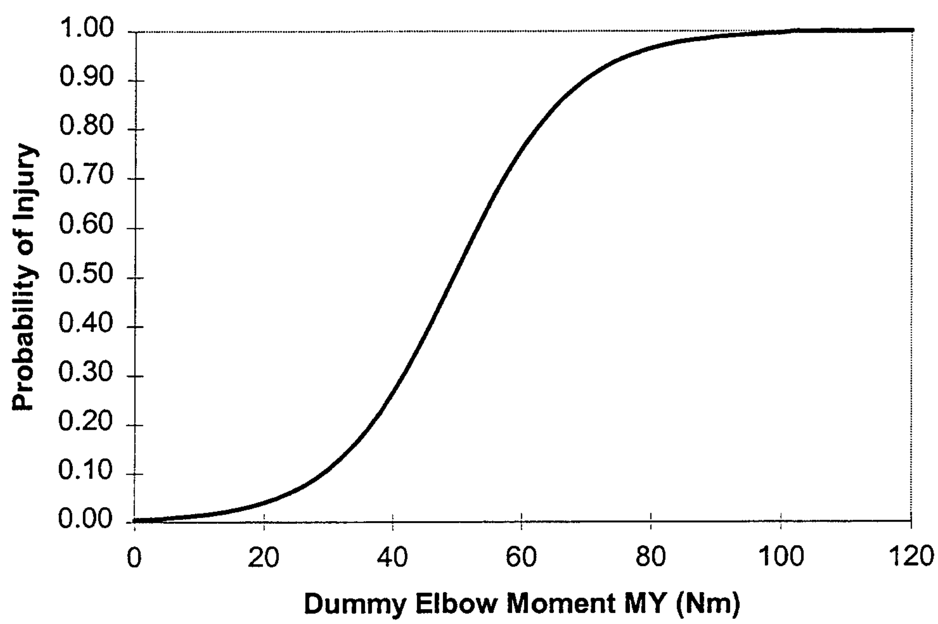

Figure 7. Dummy distal humerus moment MY injury risk curve for distal trochlear notch injuries.

The linear logistic regression analysis for the second injury mechanism, which explains the inertial loading of the elbow joint in full extension, included injuries to the proximal trochlear notch. The best correlation to injury was seen with the cadaver resultant radius acceleration ($p = 0.06$). As seen in Figure 8, the injury risk curve predicted a 50% risk of injury at 314 g's. Since these injuries are described as resulting from the 'elbow snap,' the peak dummy distal humerus moment MY, recorded when the elbow hit the joint stop, was included in the analysis.

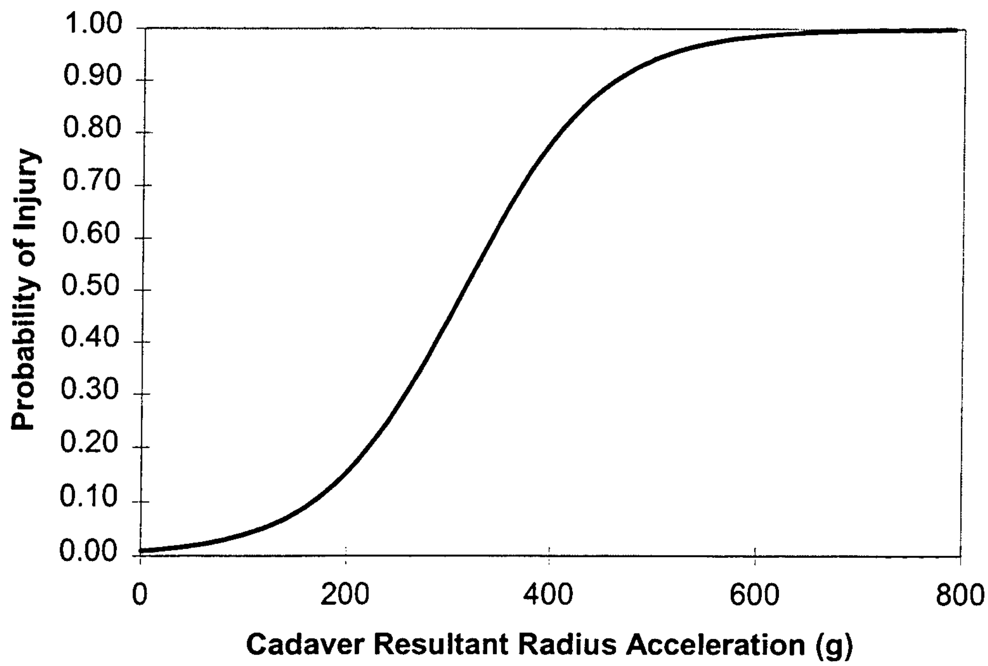

Figure 8. Cadaver radius acceleration injury risk curve for proximal trochlear notch injuries.

CONCLUSIONS

The purpose of this study was to review the literature and present the most applicable upper extremity injury criteria for the evaluation of lateral air bag loading. Due to their smaller stature and bone structure, and post-menopausal bone mineral loss, women are considered to represent the most vulnerable occupants to out-of-position air bag loading. Therefore, this study presented the injury criteria for the small female as the worst case scenario for occupants exposed to air bags. Also, more accurate criteria can be determined by utilizing data from dynamic experiments with loading rates similar to those observed under air bag loading. Given these restrictions, four injury criterion for the 5th percentile female upper extremity are established: humerus fracture criterion of 128 Nm, forearm fracture criterion of 58 Nm, and cartilage damage of the elbow criterion of 314 g's measured at the distal radius or 51 Nm measured at the distal humerus. Injury risk functions are also presented for each region. Until future research is conducted, it is suggested that the injury criteria developed from cadaver tests be used directly with the 5th percentile female dummy upper extremity in order to provide an initial assessment of injury risk.

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Predicting Airbag-Related Injury Using Anthropometric Test Devices

B. Joseph McEntire
Nabih Alem
Elmaree Gordon
Philip Johnson

U.S. Army Aeromedical Research Laboratory
Aircrew Protection Division
P.O. Box 620577
Fort Rucker, AL 36362-0577 USA

INTRODUCTION

The U.S. Army Aeromedical Research Laboratory (USAARL), Fort Rucker, Alabama, has been involved in CABS-related research for years; in fact, the original studies showing the potential benefit of a CABS in helicopters were conducted by USAARL scientists (Alem, et al., 1992; Shanahan, Shannon, and Bruckart, 1993). These analyses contributed in large part to the existing CABS programs in the UH-60 and OH-58D helicopters.

In the Army's UH-60 CABS program, a stated requirement was to demonstrate that a UH-60 aviator can maintain aircraft control during and after deployment of a prototype CABS system. This requirement stemmed from the possibility of an inadvertent deployment—that is, an unforecast and unnecessary firing of one or more airbags while the aircraft was in flight. Additional concerns were raised with regard to CABS deployment as a result of hard landings, wire/tree strikes, etc. It was recognized that airbag deployment could affect flight safety in two principal ways: aircrew injury due to CABS contact, and loss of flight control (due to many factors including surprise, interference with the flight controls, and injury). This report describes a series of studies mainly designed to quantify the risk of aircrew injury in the case of inadvertent CABS deployment.

METHODS

To examine the role of inadvertent airbag deployment in injury causation, live deployments of the prototype CABS were conducted with an instrumented anthropomorphic manikin. A series of 21 deployment tests were conducted in a stationary UH-60 aircraft, consisting of 20 individual bag deployments (5 left front, 5 right front, 5 right lateral, and 5 left lateral), followed by a complete ship-set deployment (4 bags). Various parameters were measured during each deployment test. An instrumented manikin was located in the deployment seat and placed in positions perceived to be potentially hazardous. The study used USAARL's 50th %ile male Hybrid

III manikin (for head, neck and chest measurements) and a 5th %ile female Hybrid III manikin (for upper extremity measurements; on loan from USAF) fitted with an instrumented arm (Robert A. Denton, Inc.). Descriptions of the manikin position for each deployment test are provided in Table 1.

Table 1.
Manikin positioning for air bag deployment tests.

Test name	Seat fore/aft	Seat vertical	Body position	Special condition
LLAT01	Full aft	Down	Toward bag	Collective ht = 16.5"
LLAT02	Midpoint	Midpoint	Toward bag	Collective ht = 19.7"
LLAT03	Full fore	Midpoint	Toward bag	Collective ht = 17.7"
LLAT04	Full aft	Midpoint	Toward bag	Collective ht = 21.2"
LLAT05	Midpoint	Midpoint	Toward bag	Collective ht = 19.7"
RLAT01	Full aft	Midpoint	Toward bag	Cyclic right
RLAT02	Full aft	Above mid point	Toward bag	Cyclic right aft
RLAT03	Full aft	Above midpoint	Toward bag	Cyclic right forward
RLAT04	Midpoint	Midpoint	Toward bag	Cyclic right
RLAT05	Full fore	Midpoint	Toward bag	Cyclic right aft
LFRT01	Aft	Midpoint	Leaning forward	Without NVG, head on glareshield
LFRT02	Aft	Midpoint	Leaning forward	With NVG, head on glareshield
LFRT03	Aft	Full up	Leaning forward	With NVG, looking over a/c nose
LFRT04	Aft	Full down	Leaning forward & inboard	With NVG, leaning forward & inboard, reaching for tail rotor servo control switch
LFRT05	Midpoint	Full down	Leaning forward	With NVG, leaning forward but more upright, looking at instrument panel
RFRT01	Mid	Full up	Leaning forward	With NVG, leaning forward, helmet near glare shield edge
RFRT02	Mid	Full up	Leaning forward	Without NVG, leaning forward, helmet near glare shield edge
RFRT03	Mid	Full up	Leaning forward & inboard	Without NVG, leaning forward & inboard, reaching for tail rotor servo switch
RFRT04	Mid	Full up	Leaning forward & outboard	Without NVG, leaning forward & outboard (to simulate "clearing right")
RFRT05	Full fore	Mid	Midpoint	Without NVG, leaning forward & upright, looking at instrument panel
LFULL	Aft	Up	Centered	Leaning forward & outboard, shoulders rotated outboard, helmet near A-pillar (to simulate "clearing left")
RFULL	Full fore	Midpoint	Centered	Leaning forward slightly & left arm reaching over cyclic to adjust altimeter

Several objectives were pursued during the live CABS deployment tests. The resulting manikin head accelerations, neck forces, and chest accelerations were recorded during the frontal bag deployments to determine injury risk parameters. During the lateral bag deployments, a 5th %ile female manikin with an instrumented arm was used to record arm interactions with the deploying bag. During the forward bag tests, the 50th %ile male manikin was often configured with a set of NVG, the intent being to determine if the NVG could be propelled into the manikin's face and to record the resulting impact force. Another objective was to determine the noise hazard associated with the air bag deployments.

In each test, a manikin was seated in either the pilot or co-pilot seat (Figure 1), and generally positioned such that its left hand was grasping the collective (occasionally using double sided tape) and its right hand grasping the cyclic. The flight control positions were partially dependent on the position(s) the manikin could accommodate and the position that could be maintained without a person actually holding them in place. The actual body positions tested are described in Table 1. In some instances, foam cushions were used between the seat and manikin shoulder(s) to maintain the desired position. The seat's restraint system was used and adjusted to a light tension, and the inertia reel was unlocked. The manikin was dressed in a flight suit, boots, and flight helmet. A 50th %ile male manikin was used in the frontal bag tests while a small female manikin was used in the lateral bag tests. An instrumented arm was utilized on the small female manikin to collect air bag interaction loads. Both manikins were used in the full system deployment test. In some frontal bag tests, NVG were mounted onto the flight helmet. These goggles were modified with load cells replacing the objective lens. During all bag deployments, impulse noise levels were recorded at 8 locations within the aircraft.

Figure 1. Experimental setup after CABS deployment.

RESULTS

Head and Neck Injury Assessment

Tri-axial linear accelerations at the head center of mass were measured in deployment tests conducted with the medium male MIDAS manikin (these tests involved the CABS frontal module). Resultant accelerations were calculated from the tri-axial measurements, and were then used to calculate the Head Injury Criteria (HIC). Table 2 summarizes the peak resultant acceleration value and the calculated HIC value for each test. A HIC of 1000 is associated with a 16% risk of serious brain injury. These results indicate minimal (less than 1%) risk of closed brain injury as a consequence of the prototype airbag striking the head with the manikin in the potentially vulnerable positions tested.

Forces and moments at the head/neck interface of the MIDAS manikin were measured during frontal airbag deployment tests. From these data, time history traces of neck tension, compression, flexion, extension, and fore-aft shear were extracted and assessed against the Mertz criteria. Independently, all recorded signals were within the accepted thresholds.

Chest Injury Assessment

Chest accelerations were measured in MIDAS at the mid-sternum in the anterior-posterior (Gx) and in the vertical (Gz) directions. Acceleration was not measured in the lateral (Gy) direction. The resultant of the two accelerations was computed for each test and the 3-ms, 60 G criterion applied. The absence of the lateral accelerometer was accepted since the frontal impact was not likely to produce significant lateral motion. The results (Table 3) show that one of the tests (RFRT05) failed the 3-ms criteria at 60-G.

Table 2.
Summary of head injury assessment.

Test No.	Peak Head Resultant Acceleration (G)	Calculated HIC
LFRT01	21.8	16
LFRT02	25	14
LFRT03	8.2	3
LFRT04	18.6	5
LFRT05	25.6	12
RFRT01	43	19
RFRT02	22.7	12
RFRT03	12.6	3
RFRT04	4	0
RFRT05	14.4	5
LTFULL	16.8	6

Table 3.
Summary of chest injury assessment.

Test	Peak Resultant Chest Acceleration (G)	Pulse Width At 60-G Level (msec)
LFRT01	97.3	2.9
LFRT02	88.4	1.5
LFRT03	61.7	0.5
LFRT04	18.4	N/A
LFRT05	65.2	0.8
RFRT01	48.6	N/A
RFRT02	72.8	1.3
RFRT03	28.2	N/A
RFRT04	33.3	N/A
RFRT05	118.8	4.0
LTFULL	7.3	N/A

*N/A = Resultant chest acceleration did not reach the 60-G level.

Facial and NVG-Related Injury Assessment

All assessments of facial impacts were made in out-of-position exposures. This is an area of work in which there is limited previous research. The manikins were not instrumented in the facial area; indeed no effective and validated method of instrumentation of manikins for the range of facial injuries exists. No direct measure of the forces experienced by the face was available. Four methods of estimating impacts to the face were used:

a. Impacts were recorded using high speed video for later analysis.
b. The posterior side of the NVG was dusted with chalk prior to firing to indicate contact.
c. A dummy set of NVG was instrumented with load cells in each tube.
d. The face of the manikin was examined after each impact for damage and chalk transfer.

High-speed video was of limited use, but included evidence of the early fracture and detachment of the NVG in certain impacts. The use of chalk confirmed contact with the manikin's face had occurred. Examination of the manikin's face after impact showed that on one occasion the contact was severe enough to damage the skin of the manikin's face. This must be accepted as evidence that a hard surface made contact with considerable force, as the face of the manikin is far more durable than that of the human occupant.

Analysis of the results suggests that the forces encountered in out-of-position exposures are sufficient to cause soft tissue injuries (lacerations and abrasions) to the face, and possible injuries to the eye and the orbit. These would be expected to include lacerations to the skin, lacerations and contusions to the deeper structures of the face,

fractures of the orbital floor ("blow out" fractures) and disruption of the eye itself such as lens dislocation, retinal detachment and hyphema (hemorrhage into the eye). The data imply that the forces created when the airbag deploys and impacts the NVG are likely to be too low to produce fractures of the major facial bones, but further work would be required to confirm this.

Upper Extremity Injury Assessment

The instrumented arm yielded informative results in the prototype lateral airbag deployments. Peak force and moment measurements, and associated injury risk are provided in Table 4. High risks of ulna and radius (forearm) fracture were observed during 3 of the 5 left lateral bag tests and during the full system test. These risks exceeded a 75% chance of fracture, and in one test (LLAT04), the risk exceeded 99%. The highest risk of a distal trochlear notch injury was 17% (LLAT04), and the highest risk of a proximal trochlear notch injury was 24% (LLAT03). The lateral bag interaction with the right arm did not exceed known injury thresholds. The right lateral bag did interact with the manikin's right shoulder and helmet, but the extent of this interaction is unknown since the female manikin was not fully instrumented.

There is no standard method to scale or adjust the recorded reaction loads from the small female arm to a larger male arm. Several scaling options have been proposed and are being considered.

Noise Hazard Assessment

Personnel exposed to peak impulse noise levels above 140 dB require additional hearing protection. The acoustic impulse noise measurements were dependent on bag location and sensor location. In the pilot and co-pilot crewstation, the 140 dB level was consistently exceeded. During the full system deployment, the recorded noise levels at the passenger compartment exceeded 140 dB as well. This data would require the occupants of airbag-configured UH-60 aircraft to wear a hearing protection device. Current Army policy requires passengers in the UH-60 to wear hearing protectors and aircrew to wear protective helmets which provide hearing protection. This level of hearing protection should satisfy the requirement for protection against the impulse noise levels created by the CABS system firing.

Table 4.
Summary of upper extremity injury assessment.

Test ID	Resultant forearm moment (N-m)	Risk of fx Ulna or Radius (%)	Risk of fx Ulna and Radius (%)	Flexion/ extension moment (N-m)	Risk of distal trochlear notch injury (%)
LLAT01	23.4	4.5	<1	9.3	<1
LLAT02	107.8	94.5	75	13.1	<2
LLAT03	33.4	9.5	1.3	7.2	<1
LLAT04	314.1	>99.0	>99	34.8	17
LLAT05	1187.0	98.2	88	23.2	4.5
RFULL	106.2	94.0	74	12.5	<2
RLAT01	11.4	1.5	<1	14.1	2
RLAT02	31.3	8.0	1.1	12.5	1.5
RLAT03	10.3	1.5	<1	13.6	1.8
RLAT04	5.0	<1	<1	2.5	<1
RLAT05	5.6	<1	<1	5.7	<1

Test ID	Resultant radius acceleration (G)	Risk of proximal trochlear notch injury (%)	Resultant humerus bending Moment (N-m)	Resultant normalized to IARV
LLAT01	104.0	2.7	64.4	0.50
LLAT02	195.3	14	143.7	1.12
LLAT03	97.0	24	20.5	0.16
LLAT04	194.9	14	71.7	0.56
LLAT05	160.6	8	191.9	1.50
RFULL	150.3	6.5	94.3	0.74
RLAT01	55.7	<1	49.7	0.39
RLAT02	128.0	4.5	96.0	0.75
RLAT03	108.7	3	58.8	0.46
RLAT04	***	***	9.8	0.08
RLAT05	30.2	<1	14.0	0.11

Note: Values representing "high" risk of injury are highlighted.

CONCLUSIONS

Several conclusions can be drawn from this study of an inadvertent CABS deployment scenario. First, inadvertent deployment of this prototype lateral airbag poses a high risk of injury to the left arm of an occupant seated in the left crewseat. Second, the forward airbag is potentially injurious only when the occupant is away from the usual upright flying posture. Third, an arm placed in the path of any deploying air bag is at risk of injury. Finally, an NVG interaction with the deploying forward air bag is likely to produce soft tissue injuries, but the risk of facial bone fracture cannot be assessed with the data collected thus far.

The finding that significant injury could result from deployment of this prototype CABS should not detract from other evidence that, when finally fielded, helicopter airbags will save aviator lives and reduce injury.

DISCLAIMER

The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Citation of trade names in this report does not constitute and official Department of the Army endorsement or approval of the use of such commercial items.

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Crash Protection Performance of a Helicopter Cockpit Air Bag System

Robert F. Gansman
Analytical Engineer
Simula Safety Systems, Inc.
Applied Technologies Division
7414 S. Harl Ave.
Tempe, AZ 85283
gansmanb@sssi.simula.com

Anita E. Grierson
Program Manager
Simula Technologies, Inc.
10016 S. 51st St.
Phoenix, AZ 85004
grierson@sti.simula.com

ABSTRACT

Simula Safety Systems, Inc. has been developing inflatable restraint technologies for military applications for several years. Recently, a cockpit air bag system (CABS) developed for retrofit into the UH-60A/L Black Hawk helicopter entered qualification testing. Dynamic sled tests with anthropomorphic test dummies (ATDs) were completed under a variety of crash conditions. Results demonstrated a significant reduction in the head and torso flail that now leads to serious or fatal injuries in severe crashes. Injury protection was further demonstrated by low ATD loads and low injury probabilities for the head, neck, and chest. These good results were obtained despite the design constraints and tradeoffs required to make the system work in a retrofit application.

INTRODUCTION

Work to improve the crashworthiness of military and civil helicopters has been progressing for years. Efforts began with implementation of fuel tanks that resist post-crash fires, and have included innovations like improved restraint harnesses, locking inertia reels, stroking seats, and energy absorbing landing gear and aircraft structure. These devices have eliminated most debilitating and lethal injuries from high spine loads, crushing, impaling, and post-crash fires in survivable crashes. Now most serious injuries are caused by secondary impact of the head and upper body on cockpit interior objects (Zimmerman, et al., 1989). Inflatable restraints like the CABS can reduce or eliminate these types of injuries and further extend the threshold of aircrew survival (Shanahan, et al., 1994). Simula Safety Systems has been developing inflatable restraints for several years, and recently began qualification testing of a CABS for the UH-60A/L helicopter (Smith and Desjardins, 1998).

DESIGN CONSTRAINTS

Designing an effective air bag system involves taking tradeoffs and accepting constraints to achieve a system that satisfies the many often-conflicting requirements. Some difficult issues arise from the need to retrofit air bags into existing aircraft, without the flexibility to optimize all of the subsystems that contribute toward occupant restraint. A complete restraint system might include inflatable belts or air bags, an energy absorbing seat that strokes under crash loading, a four or five point restraint harness, and a locking inertia reel. All of these components work together to control flail and limit loads on the body, and each could be adjusted to optimize overall performance. But when retrofitting an air bag system there is no opportunity to modify the existing components; their operation must be taken as a design constraint. This is not a small concession, as the different components offer good opportunities for optimization through a systems approach. For example, the seat and restraints can be modified to incorporate energy absorbing components that decrease loads on the torso, while air bags mitigate the extra flail that would otherwise occur.

Another important consideration is the location of the forward air bag module. It needs to be in front of each occupant and centered on the body to allow use of simple symmetric bag designs that deploy quickly, with minimal trajectory deviations and a high tolerance to angled crashes. But in a retrofit the helicopter instrument panel and glare shield were not designed to incorporate air bag modules. Space front and center is the most valuable real estate on the instrument panel, and helicopter designers are understandably concerned about relocating instruments and displays, or allowing the air bag modules to degrade instrument visibility. Visibility above the glare shield is also important for flying, and the module cannot intrude significantly into this space. An acceptable compromise must be reached.

Air bag size and compatibility with aviator equipment is another concern. Aviators increasingly fly night missions with night vision goggles (NVGs) attached to the front of their helmets. Should a crash occur in this mode of flight, the deploying air bags must not drive the goggles into the face, possibly causing severe injuries. This requirement effectively limits the height of the air bags to that which will deploy beneath the goggles, lifting them up and away from the face. The bags must also avoid catching on the top of the cyclic control sticks for proper performance, limiting size and shape options for the lower part of the bags, and posing a challenge in achieving the proper deployment trajectory.

A final consideration is the need for extended inflation. Helicopter crashes often involve skidding, bouncing, rolling, and tumbling that extend the time that injury protection must be provided. Extended inflation requires sealed bags and special inflator designs to generate gas at lower temperatures or for longer periods of time. But the air bags cannot remain fully inflated indefinitely because they could obstruct rapid emergency egress from the cockpit, an important factor in post-crash survival. Sealed bags also induce higher loads on the occupants than vented bag designs, which provide a greater ride-down

effect. But venting the bags, given the geometric constraints in a cockpit and the need to design for the full anthropometric range, may allow the occupant to bottom out and sustain a strike through the bag.

UH-60A/L CABS DESCRIPTION

The UH-60A/L CABS design represents a compromise that takes into account all of the previously discussed tradeoffs and constraints. The system consists of an electronic crash sensing unit (ECSU), two forward air bag modules, two lateral air bag modules, interconnection wiring, and mounting hardware. The forward modules mount in rectangular shaped cutouts in the glare shield, and protrude partly above and partly below it to balance the impact on visibility through the windscreen with instrument panel viewing. The modules are located about four inches inboard of center on each occupant. This location is not the best for air bag performance, but is required to minimize the impact on field of view above the glare shield. To accommodate the off-center location, the bags are slightly asymmetric, and the modules are angled outboard toward the occupants. The forward bags are about 60 liters in volume and shaped to fit in the space between the cyclic stick on the bottom and NVGs on the top.

The lateral air bag modules mount on the side armor panels outboard of each occupant. The bags are oval shaped and about 4-in. thick. They deploy forward, from near the shoulder, to touch the end of the forward air bags, enclosing the corners of the cockpit. A 60-liter bag was evaluated in this test series; the volume being chosen to allow use of the same gas generator in both the forward and lateral modules. All bags, both forward and lateral, are sealed to maximize inflated bag volume while the inflator gases cool, providing functional protection for as long as possible. The bags partially deflate as they cool, and quickly reach a volume that testing showed would not hinder egress.

The ECSU contains orthogonally mounted accelerometers that sense the aircraft acceleration environment in three dimensions. Crash discrimination software applied to the acceleration measurements determines if a crash is occurring. The unit releases stored energy to initiate the inflators and begin bag inflation in a crash. Internal backup power ensures continued ECSU function if aircraft power is lost. Data recording stores the accelerations to aid crash investigation and provide design information for future enhancements, like advanced discrimination algorithms. An earlier design of the ECSU is described in a recent paper (Gansman and Derouen, 1999). Since then, the unit has been improved to eliminate single point failures for higher reliability, and to replace the backup power batteries to further increase reliability and extend the operating temperature range.

DYNAMIC TEST RESULTS

Test Fixture

The dynamic tests were conducted in a mockup of the UH-60A/L cockpit. The mockup recreates the critical geometric features, allowing realistic occupant locations and accurate distances between the occupants and the most common strike hazards. Common

strike hazards include the instrument panel, cyclic and collective sticks, side armor panel, and certain structural members. Instrumented ATDs are seated in the mockup to allow observation of head and body flail and air bag interaction, and to provide data for a quantitative injury assessment. Actual seats are used to provide adjustment for different sized ATDs and to allow correct stroking of energy absorbing components. A glare shield modified to hold the forward air bag modules fits over the instrument panel.

Test Conditions

The CABS is generally not needed in low severity crashes because the existing five-point restraint, stroking seat, and inertia reel satisfactorily restrain the occupants and prevent injuries in these minor impacts. The CABS is needed in the high severity crashes where the existing restraints can't limit head and chest flail enough to prevent the secondary strikes that lead to injuries. The crash conditions (characterized by peak deceleration and total velocity change) for dynamic testing are based on studies of actual accidents, and are chosen to represent the most severe survivable crashes (Shanahan and Shanahan, 1989). A survivable crash is one in which the aircraft structure provides a protected space that would allow survival, regardless of whether the occupants actually survived.

Performance Assessment

A complete description of the injury assessment procedure used during CABS development was recently published (Grierson, et al., 1998). Since the primary goal of the air bag system is to eliminate head and chest contact with strike hazards, the performance assessment relies heavily on visual indicators like bag inflation timing and flail observations in high speed video. Baseline tests, the same severe crashes without air bags present, are also used to indicate the relative improvement with CABS. And injury assessment criteria based on the ATD load measurements are used to gain further insight into the air bag system's operation. The injury assessment criteria allow a quantitative indication of whether the CABS has reduced body loads to an acceptable level of risk. Using this full complement of data, safety enhancement predictions and the associated cost-benefit decisions can be made.

Because of the complexity of the military helicopter environment, the CABS has undergone a more extensive evaluation than currently required for automotive, military, or civil aviation restraint systems (including air bags). The Federal Motor Vehicle Safety Standard requires a commercial automotive restraint system to pass one forward crash test (FMVSS 208) and one lateral test (FMVSS 214) for side impacts. Certification of restraint systems for civil aviation requires two tests, each in a different orientation (SAE AS8049). Certification of military restraint systems requires four tests in three different orientations (MIL-S-58095). To date, the CABS has completed 15 dynamic tests in five different configurations during qualification.

This paper presents a subset of the injury assessment data that represents typical operation of the CABS. Evaluations of the ATD data are made using risk curves from the literature. These curves show the probability that a human would sustain a serious

(AIS>=3) head, neck, or chest injury based on the measured ATD loads (Mertz et al., 1997). The risks for skull fracture and brain injury are based on the Head Injury Criterion (HIC). The neck injury risks are for loading in combined tension and extension, the mode that consistently produced higher risks than the other combined modes of neck loading. The chest injury risks are based on both the sternum deflection to represent crushing injuries, and the viscous criterion to represent soft tissue injuries (Viano and Lau, 1986). These curves are not perfect, as injury assessment is not fully understood and remains an active field of study. But they are based on the best available knowledge, and provide an easily understood method for interpreting the meaning of measured ATD loads.

Forward Test Condition

The forward test condition is conducted with the mockup mounted on a horizontal sled and the occupants facing straight forward toward an impact barrier. The sled is slowly accelerated and then rapidly decelerated against the barrier to simulate a crash. The sled deceleration, or crash pulse, is approximately triangular in shape with a 28 to 32 G peak and a total velocity change of at least 50 ft/sec. This test condition verifies the crash sensor thresholds, air bag inflation timing, flail reduction, and protection from the forward strike hazards. A baseline test was conducted to quantify the change in ATD dynamics, and to give a visual indication through high speed video of the amount of flail that occurs when no air bags are present. Several tests with the CABS were completed to verify system operation and establish the repeatability of the data. All tests were conducted with the 50th-percentile size ATD.

Figure 1 shows a top view of the cockpit mockup with the pilot and copilot ATDs at maximum forward head flail in both the baseline and CABS tests. The tops of the helmets are marked with a white cross and optical target. The NVGs are marked with optical targets. The baseline test showed the head flailing forward until contact was made with the flexible glare shield. The head then continued below the glare shield into the hazardous region near the instrument panel and cyclic stick. This large flail occurred despite five point restraints and automatic locking inertia reels working as designed. In the CABS tests, the forward and lateral air bags deployed to restrain the flail, keeping the head well above the glare shield and away from the instrument panel. The NVGs can be seen on top of the glare shield moving forward. The bags deployed beneath the NVGs, lifting them up and away from the face and avoiding facial contact.

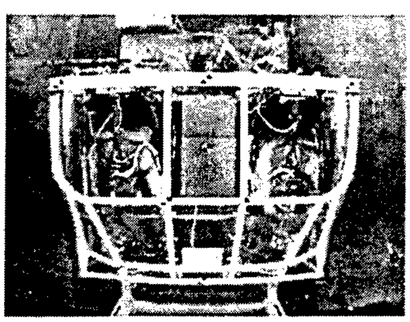

Figure 1. ATD flail in baseline.

Table 1 shows typical injury assessment results for the forward tests. Each test included both a pilot and copilot ATD. An asterisk in the table shows where no data was acquired, due to instrumentation failure or to some other problem that invalidated the results. The CABS data shows relatively little scatter indicating good repeatability. The injury assessment data shows only a small improvement in the neck injury risk over the baseline condition. All other risks remain negligible.

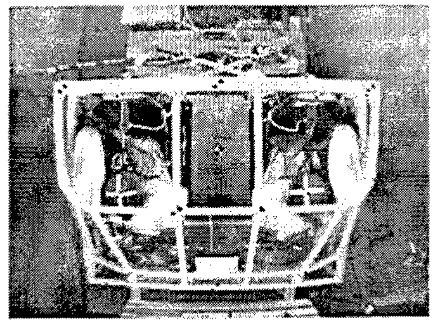

Figure 2. ATD flail restrained by CABS

Table 1 – Injury Assessment Results for the Forward Test Condition

Test	Head Injury Risk (%)		Neck Injury Risk (%)	Chest Injury Risk (%)	
	Skull Fracture	Brain Injury	Tension-Extension Loading	Deflection	Viscous Criterion
39-copilot	5.3	4.6	4.4	0.0	0.5
39-pilot	2.8	2.2	3.6	*	*
40-copilot	6.3	5.7	3.8	0.0	0.6
40-pilot	4.0	3.4	4.4	*	*
Baseline Test With No CABS					
43-pilot	2.0	1.5	20.0	0.0	0.5
43-copilot	1.7	1.2	11.0	*	*

At first, the small change in injury results between baseline and CABS may seem to suggest that the CABS is not needed. But it is important to remember that the primary goal of the CABS is to reduce head and chest flail, and the video record consistently shows a dramatic flail reduction with CABS. The system is providing a critical function that cannot be evaluated with ATD measurements alone, especially in a sled test that does not reproduce the structural crushing, deformation, and intrusion of objects into the cockpit that occur in a real crash. By restraining flail, the CABS can protect from injuries induced by these hazards. The ATD data does provide valuable information - the low risks with CABS indicate that flail reduction has been obtained without introducing new severe head, neck, or chest injury risks.

Vertical Test Condition

The vertical test condition is the most severe, with a peak deceleration of 45 to 50 g and total velocity change of at least 50 ft/sec. Its severity is dictated by the excellent crashworthiness of the UH-60 helicopter, in which hard crashes are needed to reach the limit of survivability. The deceleration pulse has a long duration, low-g region that simulates stroking of the energy absorbing landing gear, followed by the high-g impact region. The cockpit is pitched down 30-deg and dropped vertically in a drop tower. The

pitch-down orientation creates the forward component of the crash force that would occur in a high speed ground impact, and is not intended to represent a specific aircraft orientation. The test ensures that the air bags will prevent head and chest contact with the cyclic stick and instrument panel in the most severe survivable crashes.

A vertical baseline test was conducted in a half-cockpit mockup that allowed a good side view of ATD motion. Figure 3 shows two stills from the high speed video. The first still shows the ATD in normal position at the instant of impact. The helmet has a white stripe down the side and NVGs are mounted in front. The cyclic stick is between the legs and is gripped by the right hand. In the second still the head has moved down and the face has squarely struck the cyclic stick. The strike occurred despite a restraint harness and inertia reel working as designed. The test confirmed that head flail into this region of the cockpit (below the glare shield and near the instrument panel) can result in serious injuries, and also confirmed that the chosen test condition is severe enough to produce injuries consistent with those documented in field studies of actual crashes.

Figure 3. Initial ATD position at impact (left) and face strike with cyclic stick

A series of vertical tests with the CABS was conducted in the full cockpit mockup to demonstrate the injury protection performance. Figure 4 shows a still from the high speed video after the bags have deployed, when the ATD head has loaded the bag and the seat has just started stroking. The top of the helmet is marked by a white cross. The pilot side is shown. The forward air bag has restrained the head from flailing below the glare shield as it did in the baseline test. The bag has deployed beneath the NVGs lifting them safely away from the face. Beyond this point in time, the ATD is pulled down by the restraints attaching it to the seat as the seat strokes about 12 inches (as designed to limit the lumbar loads). The head is pulled down by the torso and goes out of camera view.

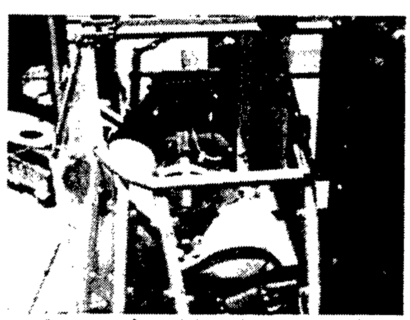

Figure 4. Pilot head restrained by forward air bag in vertical test

Table 2 shows typical injury assessment numbers for the vertical test condition. The data shows moderate injury risks for the tests with CABS, and a dramatic reduction in injury risks from the baseline test where a head strike to the cyclic stick occurred. The full set of data showed scatter, which can be attributed to sensitivity of the ATD motion to the initial position, and is aggravated by the vertical stroking of the seat.

Table 2 – Injury Assessment for the Vertical Test Condition					
Test	Head Injury Risk (%)		Neck Injury Risk (%)	Chest Injury Risk (%)	
	Skull Fracture	Brain Injury	Tension-Extension Loading	Deflection	Viscous Criterion
33-copilot	2.5	1.9	0.9	0.0	0.3
33-pilot	2.2	1.7	0.4	*	*
Baseline Test With No CABS					
DV-pilot	55.0	61.0	58.0	*	*

Forward With 10 Degree Yaw Test Condition

The forward test condition with 10-deg yaw is conducted between 19 and 22 G with at least 42 ft/sec velocity change. The test fixture is yawed 10-deg to project one occupant inboard and one outboard slightly. The test condition represents a severe but more common crash scenario, and was chosen to evaluate different sized occupants including the 5th-, 50th-, and 95th-percentiles.

Table 3 shows typical injury assessment results for the 10-deg yaw test condition. In all tests the CABS properly restrained the head and chest and significantly reduced flail. The NVGs safely detached without contacting the face. The injury risks for the 50th and 95th-percentile occupants remained insignificant in either position (pilot or copilot). Testing and evaluation of the 5th-percentile occupant is not yet complete.

Table 3 – Injury Assessment for the 10-deg Yaw Test Condition					
Test	Head Injury Risk (%)		Neck Injury Risk (%)	Chest Injury Risk (%)	
	Skull Fracture	Brain Injury	Tension-Extension Loading	Deflection	Viscous Criterion
50-copilot (50th)	0.5	0.3	1.0	0.0	0.3
50-pilot (50th)	0.4	0.2	1.1	0.0	0.2
48-pilot (95th)	0.8	0.5	1.0	*	*
47-copilot (95th)	0.5	0.3	1.1	*	*

CONCLUSIONS

The UH-60A/L CABS has been subjected to one of the most extensive occupant injury evaluations conducted for a new restraint system. In several tests covering a range of impact conditions, the CABS repeatedly showed significant reductions in the head and torso flail that field data has proven cause the serious and fatal injuries in severe crashes. The ATD data also showed low injury risks for the head, neck, and chest in impact tests conducted at the limit of survivability. These results are especially encouraging given the design tradeoffs that prevent a complete system optimization to minimize the ATD loads.

ACKNOWLEDGEMENT

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BIOGRAPHIES

Mr. Gansman has worked on inflatable restraints at Simula for three years in the areas of system level design, crash sensing, and injury assessment. Previously he worked five years in computational fluid dynamics, heat transfer, and combustion system design for the Babcock and Wilcox Company. He holds an M.S. and B.S. in Mechanical Engineering from North Carolina State University.

Ms. Grierson has worked at Simula for five years as a Program Manager and Biomechanical Engineer. She developed an injury assessment protocol for helicopter air bag systems, led a design team in development of a new transport aircraft seat, and led an investigation of injury mechanisms and prevention in aircraft accidents. She holds an M.S. in Mechanical Engineering from Northwestern University and a B.S. from the University of Michigan.

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Inflatable Restraints in Aviation - A UK Military Perspective

Les Neil
Senior Engineer-Impact Protection
Defence Evaluation and Research Agency
Farnborough UK

ABSTRACT

Many reviews of helicopter accidents have recommended further investigations into more effective crew restraints to improve protection in the event of an accident. The Inflatable Body And Head Restraint System (IBAHRS) is one method of offering additional protection for occupants in such cases.

IBAHRS was developed in the USA where dynamic crash tests were conducted to assess performance prior to its first application. In the UK, the Centre for Human Sciences (CHS) has assessed the responses of male and female test dummies, during simulated impacts using a system manufactured by Simula Inc. These tests showed that reductions in forward head and shoulder displacement could be achieved, confirming that IBAHRS offers an improvement in occupant-seat coupling during a mishap. Additionally, static integration assessments using male and female volunteers have highlighted IBAHRS interaction with the commonly used UK Aircrew Equipment assemblies (AEA). Work has also addressed the feasibility of computer models to simulate the performance of inflatable restraints, the ability of occupants to escape from a submerged cockpit and the performance of IBAHRS during ejection test tower trials.

Investigations are continuing in support of a possible UK-designed inflatable restraint system, along with assessments of novel sensing and inflation methods.

INTRODUCTION

Developed in the USA, the Inflatable Body And Head Restraint System (IBAHRS) consists of inflatable airbags which are folded around the shoulder straps of an aviator's conventional 5-point harness assembly. When an impact to the aircraft is sensed a gas generator, which is built into each of the airbag vessels, rapidly inflates each airbag. This has the effect of improving the coupling between the occupant and the seat, thereby, reducing the overall motion of the occupant's torso and head during the impact. This in turn reduces the overall likelihood of the occupant's head or limbs striking the surrounding structures in a helicopter cockpit.

Dynamic Impact Trials

In the UK, the Royal Air Force Institute of Aviation Medicine (RAF IAM) felt that the potential for improving the effectiveness of the shoulder restraint in a 5-point restraint equipped with IBAHRS was worth investigating at the

same time as the influence of Night Vision Goggles (NVG) on the dynamic response of the head and neck [1]. A set of airbags was obtained from the Naval Air Development Centre (NADC) in order to explore these effects of better shoulder restraint on the dynamic response of the neck of a 50th percentile Hybrid III test dummy.

Results of these early trials showed that in Gx impacts, reductions in forward head displacement of up to 50% could be achieved by the use of IBAHRS. Reductions in forward head displacement of up to 38% were also achieved in Gz impacts. Figs. 1 and 2 show head trajectory plots recorded during 12Gx impacts with and without IBAHRS. However, it became clear at an early stage that impacts above 12G were causing damage to the NVG, as the goggles themselves were not designed to withstand the inertial loads associated with accelerations in excess of 10G. In addition, slippage of the aircrew helmet on the dummy's head was making analysis more difficult. Therefore, it was decided to discontinue this series of impact runs.

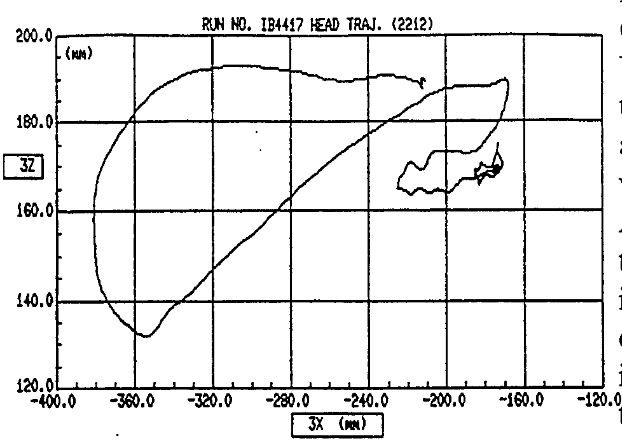

Fig.1 Head trajectory plot with IBAHRS

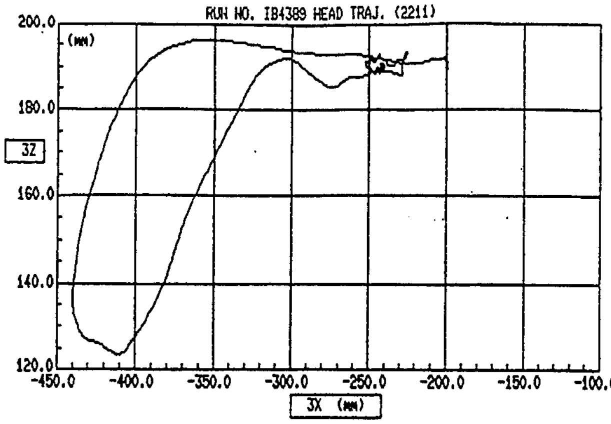

Fig. 2 Head trajectory plot without IBAHRS

At the time of these UK assessments, the US Navy and Simula Inc, Phoenix, USA were carrying out a design review to solve problems experienced with systems of this type. Issues such as fouling of the airbag during inflation, separation of the airbag from the host harness during inflation, and airbag shape and size were investigated. The review led to several design changes to the airbag and harness attachments, resulting in the IBAHRS Critical Design Review (CDR) version. Fig. 3 shows an IBAHRS CDR system deployed on a 50th percentile test dummy.

Although a fully operational IBAHRS CDR had been dynamically tested by the US Navy [2] it was nevertheless necessary to ensure that the system continued to afford improved restraint when worn with UK Aircrew Equipment Assemblies (AEA), and that the airbags themselves presented no adverse interaction with flying clothing and equipment. Therefore, further dynamic impact tests and dynamic integration trials [3,4] were carried out on the decelerator track at the Centre for Human Sciences (CHS), Farnborough,

using IBAHRS CDR systems supplied by Simula.

Results of these evaluations, which utilised several sizes of Hybrid III test dummy, again showed that an IBAHRS system affords improved restraint, compared with a standard UK 5-point restraint. However, interaction of the airbag vessels occurred with several items of AEA such as the commonly used Mk25 Life Preserver (LP) resulting in a tendency for the harness shoulder straps to move laterally towards the edge of the shoulders of the occupant, particularly where a 5th percentile female dummy was used.

Fig.3 IBAHRS CDR system deployed

Integration with UK Aircrew Equipment Assemblies (AEA)

Further investigation [5] addressed the degree of any interaction between IBAHRS and typical AEA worn by British aircrew in rotary wing aircraft under static (non-crash) conditions. Test subjects, 4 male and 3 female, wearing 4 combinations of AEA were asked to demonstrate their ability to egress from a restraint fitted with IBAHRS after inflation. Any interaction of the AEA during inflation of the airbags was noted. Video coverage of each subject's egress showed that normal egress from the 5-point host harness was not affected by inclusion of the IBAHRS. However, there was an increase in the effort required to operate the harness Quick Release Fitting (QRF) along with several occurrences of helmet lift and interaction with the LP and Short-Term Air Supply System (STASS) bottle.

During these human static integration assessments, one subject, who was a helicopter pilot/medical officer, commented that an inadvertent inflation of the IBAHRS during flight could affect the pilot's ability to control the aircraft. His comment was based on his belief that both the surprise element of the bags inflating unexpectedly, and the pressure of the airbags on the aviator's chest, may cause loss of concentration or mobility and, therefore, lead to a mishap. Additionally, interaction during an inadvertent inflation, between the airbag vessels and an aviator's helmet fitted with NVG, may cause misalignment of the optical tubes of the NVG during night flying.

During all the assessments the effort required to operate the US-style Quick Release Fitting (QRF) was higher with the IBAHRS CDR airbags inflated than with the airbags stowed, due to the pressure inside the airbags tensioning the shoulder straps of the harness. Although it was possible to release the QRF after every inflation during these

assessments, the extra effort required to release the harness may have implications for the ability of an aviator to escape during an emergency. A UK application of IBAHRS would need to conform to the relevant UK Defence Standard [6] for harness assemblies, and so may not necessarily use QRFs of the type used in this assessment. However, trials addressing the implications of these increased loads were considered necessary, whichever type of QRF was used.

Computer Modelling

In support of these assessments a computer model [7,8] was developed by the Cranfield Impact Centre (CIC). The computer models created during this study were used to recreate the interaction with IBAHRS NADC airbags and the Mk25 LP, with a view to investigating any possible design changes to the airbags which may reduce interaction. In addition to modelling the IBAHRS NADC airbags, dimensions and inflation characteristics of the IBAHRS CDR airbags were also modelled to provide data which would allow the model to be validated against data obtained during the dynamic assessments. Fig.4 shows a typical computer model output generated to simulate a 10Gx impact.

This use of computer models to assess the performance of IBAHRS requires the use of innovative modelling. Unlike the techniques used in the modelling of automotive airbags, there is more interaction between the occupant, the harness and the airbag itself. This is because during the inflation of the airbag and during the impact, contact points between the inflating airbag and the occupant are constantly changing. In order to model the effectiveness of IBAHRS, the modelled airbag has to be 'draped' over the occupant model to ensure that the restraint will continue to be in the same position as it is in the dynamic assessments. Therefore, each time the model is modified to include additional items of AEA, contact points have to be redefined. This application of computer modelling has tested the capabilities of the LS-DYNA3D Finite Element (FE) software used. Resulting in increased computer processing time for each animation sequence produced.

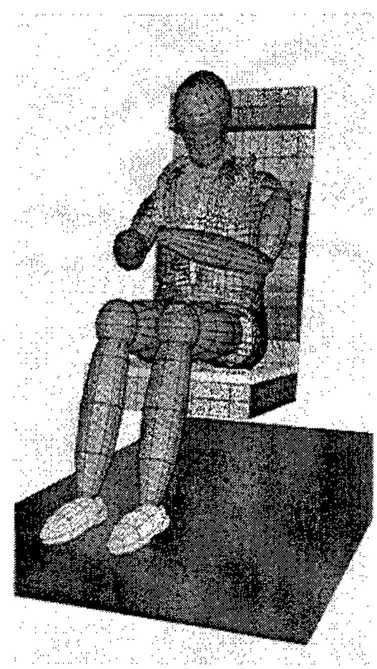

Fig.4 Typical computer model output of 10Gx impact

Following these IBAHRS CDR assessments, modifications were made to the airbags to remove those portions that had been seen to interact with the LP and STASS. This resulted in a

smaller, squarer airbag which was subsequently assessed during further dynamic impact assessments. These assessments showed that airbag interaction with the stole portion of the LP has been reduced by using the reshaped airbag. However, it was concluded that there was still a risk that the STASS bottle might be displaced enough during a real mishap or impact to have an effect on an occupant's ability to carry out a subsequent successful underwater egress. Additionally, in the panic that ensues in an underwater escape, the mere fact that the STASS bottle may not be exactly in the expected position in the pocket, may also lead to confusion and possible hindrance or failure of a successful emergency egress.

Underwater Egress Assessments

In order to assess the effect that the different shaped airbag vessels of an inflatable restraint may have on the ability of an occupant to carry out a successful underwater egress, a trial [9] was carried out using a side-by-side, pilot and co-pilot, seating arrangement in a Merlin helicopter-configured underwater escape demonstrator. Six subjects wearing aircrew helmets and Mk25 LP fitted with STASS bottles, were asked to demonstrate their ability to successfully locate and use their STASS bottle, operate their QRF, release themselves from their inflatable restraints inside the demonstrator, and carry out a successful egress while in both an upright and inverted configuration.

On completion of the strapping in procedure by each subject, the demonstrator was lowered into the water. Just as the demonstrator touched the surface of the water, a safety diver on board initiated the inflation of the restraint systems by operating a valve which allowed the contents of a CO2 non-refillable cylinder to be released into the airbags.

After full inflation of the airbags had been achieved, subjects began their egress attempt, paying particular attention to their ability to operate their QRF assemblies and the effect that the inflated airbags had on their ability to release themselves from the seat. Fig.5 shows a view of a subject effecting an egress from the simulator. On the occasions when a STASS was used, subjects demonstrated their ability to locate and use the STASS bottle. Following each immersion, subjects' comments were recorded, along with any observations made by the safety diver inside, or observer outside, the demonstrator.

Fig. 5 Subject egress from Merlin helicopter simulator

From this underwater assessment, it is clear that the inflatable restraint system airbags, whatever the shape, interact

with the STASS during egress attempts from a submerged aircraft. However, at no time during the assessment was a subject prevented from making a successful egress by the operation of the restraint systems being assessed. All subjects were able to release themselves from their QRF, locate their STASS, and effect a satisfactory egress.

On four occasions when, on release of the QRF, the STASS lanyard snagged the inflated airbags, the egress of the subjects was hindered due to the need to untangle the lanyard. During the inflation of the airbags, the subjects were seen to reach over and around the airbag in their attempt to locate the STASS bottle. However, in the process of pulling the STASS bottle to their mouth, they pulled the bottle over and across the inflated airbag. In each case video evidence showed that, on release of the QRF, the size and extra buoyancy of the inflated airbag carried the lanyard away from the subject. As both ends of the lanyard are effectively attached to the subject, it was necessary to 'thread' the airbag between the subject's torso and the lanyard. It is noteworthy that during eight other egress attempts where a STASS was used, the subjects can be clearly seen pulling their STASS bottle downward and around the lower edge of the inflated airbag, before raising the bottle to their mouths. In these cases, snagging of the lanyard with the airbags did not occur when the QRF assemblies were released. This suggests that, the problem of snagging during an underwater egress could simply be solved by a modification of the underwater training procedures.

Several subjects commented that the unexpected physical sensation of the airbag pressure and the associated tightening of the harness on their chests caused 'winding' which resulted in difficulty in breathing while using their STASS underwater. In addition, subjects indicated that it was common practice for occupants to hold onto the airframe during an underwater egress attempt as it helps to maintain a level of orientation inside the cockpit whilst underwater. However, on the two occasions where subjects, while inverted, had to push the inflated airbags out of the way with their hands, loss of orientation was experienced during the egress attempt. Although loss of orientation could be experienced during any underwater egress attempt, even when using a conventional 5-point harness, the airbags remaining in place on the occupant's chest after release of the QRF may offer an additional distraction.

It is considered that any inflatable restraint system that is brought into service could incorporate designs of future smart sensors which could detect the presence of water following a water impact. This would enable the inflated airbags to remain inflated in order to protect the occupant from the inertial effects of the impact, but then deflate when underwater, thus removing the pressure on the occupant's chest, allowing him to inhale and exhale more easily while using the STASS. Additionally, the deflation of the airbags may help alleviate interaction with the STASS lanyard, reducing the risk of snagging.

Use of IBAHRS During an Ejection Sequence

Following the dynamic impact trials which highlighted the positive effect that IBAHRS had on reducing head and torso displacement, there appeared to be value in assessing whether such a system could help restrain the torso in the initial phases of an ejection sequence. It was considered that an IBAHRS system may help the occupant attain a more favourable posture during the sequence thereby reducing the risk of spinal injury. Therefore a simulated ejection trial [10] was carried out on an ejection seat test tower to determine the effect of IBAHRS on the response of an aerospace 50th percentile Hybrid III dummy fitted with the capability to measure spinal loading.

A pair of IBAHRS airbags were fitted to a standard Simplified Combined Harness (SCH) which was modified to accept the fixing screws and spreader plate which were fitted as an integral part of the airbags. The harness was then fitted to the Martin Baker type 10B ejection seat on the test tower rails.

The trial showed that the addition of IBAHRS reduced the forward flexion of the body in the initial stages of an ejection sequence and that a decrease in thorax forward acceleration produced a corresponding increase in lumbar load Fz as the vertical component the ejection force. Nevertheless, as forward flexion has decreased the increased lumbar load acted on a larger surface area of the spinal column. Figs. 6 and 7 show dummy Lumbar Fz loads and Thorax Gx accelerations recorded during test ejections with and without IBAHRS.

Without an accurate, multi-axis mathematical model of the spine, it is difficult to analyse the effect of decreasing thorax Gx and increasing lumbar Fz and to relate these data to spinal injury risk. Consequently, the change in spinal loading due to the addition of harness mounted airbags is difficult to relate to spinal injury. In addition, any changes to loading of the neck were studied. Any potential to reduce spinal injury would be tempered if the addition of an airbag system merely transferred the injury potential to the neck. However, the addition of airbags had no apparent effect on loading of the neck or head during the initial ejection sequence although loading to the head on impact with the head box could not be accurately assessed as the dummy did not replicate head / head box impact throughout the trial.

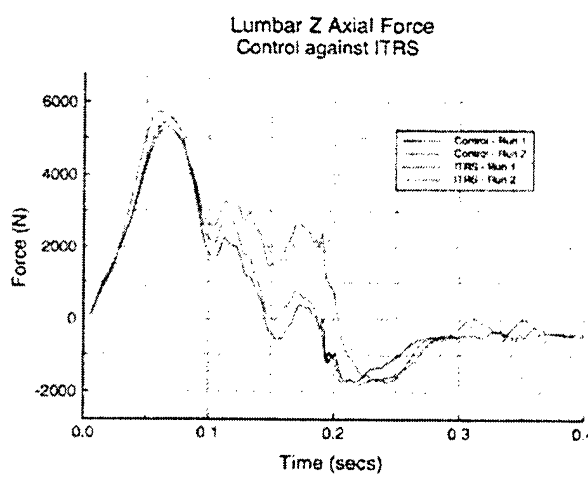

Fig. 6 Lumbar loads recorded during test ejection sequence.

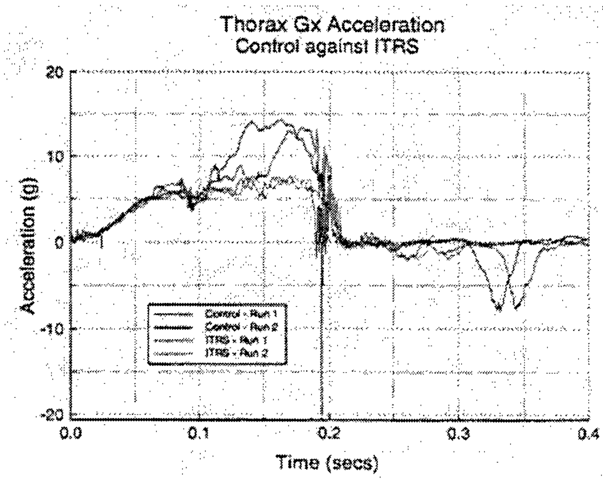

Fig. 7 Thorax accelerations recorded during test ejection sequence

Future UK Military Investigations

It is proposed that further investigations will address the problems encountered in previous UK assessments. A new inflatable restraint system that will incorporate a number of novel design concepts is being considered to meet the special requirements for aviation applications.

It is proposed that the harness airbags will be integrated with a collar bag which is separated from the main bags by means of a flapper valve. When the crewman comes forward under impact the bags and harness limit his movement. Gas in the bags will then be compressed and will flow through the valve and inflate the collar portion. This will then deploy behind the crewman's head thus limiting the degree of backward travel and hence injuries from whiplash.

In addition, a compact bottle opening system based on a pyro-mechanical piston actuator may be used to interface the pressurised gas assembly with the proposed airbag system. This actuator is compact but extremely powerful and contains a small quantity of pyrotechnic. It is further proposed that a second actuator will be introduced which can operate a gas release mechanism which is able to deflate the airbags. This activation can be initiated by time delay after impact or by a water activated power source.

Inflation Methods

With increased awareness of the need for occupant safety, whether by users in the automotive industry, the aviation industry, or in motorsport, many novel ideas have emerged for more efficient airbag-based methods of occupant protection. While these users may have their own unique requirements of a safety system, the one aspect common to every airbag-based supplementary restraint is the need to detect the impact and inflate the airbag before the impact has an inertial effect on the occupant. Unique to the aviation environment is the fact that, in addition to having to sense an impact in many more axes, potentially survivable impacts with the ground may follow a period where an aviator may be able to take pre-emptive action.

So far, the method of inflating the airbags has not been examined by the CHS. Production IBAHRS CDR systems utilise gas generators which rapidly inflate the airbags. For all IBAHRS dynamic impact trials carried out at the CHS, a method of inflation using stored air was utilised. Chambers connected to each airbag via electrically operated solenoids, were charged before each impact and an electronic sensing circuit enabled a control box to open

each solenoid valve thus allowing the air in the chambers to be released into the airbags. Circuits were also built into the system to control the time delay between the sensor passing over the trigger plate fixed to the track and the vehicle touching the arrestor cables. By using this method the inflation sequence could be finely controlled to eliminate the time taken for the sensor circuit and the solenoids to operate.

The use of gas generators is accepted by the automotive industry as the most effective method of inflating airbags rapidly during an accident or impact in which an occupant is to be protected. However, compressed air technology is advancing rapidly and there is now some possibility that the inflation times of small airbag systems like IBAHRS could be met by the use of miniature compressed air vessels. Discussions with ICI have identified a possible source of this type of technology which, if suitable, could contribute to future airbag restraint assessments. However, further work into this aspect of inflatable restraints is required.

Crash Sensing Methods

In automotive applications, the operation of an occupant restraint is triggered by an event such as an impact. This requires safety systems which are capable of operating rapidly enough to sense and operate before an occupant is put in a position of likely injury. However, advances in technology now permit motor manufacturers to consider the use of smart sensors. These sensors are able to record inputs from other components of the car to determine the velocity of the car, distance of the car from a likely impact point, and the rate of change of that distance. On-board computers can then decide whether the occupant restraint should be operated before an impact actually occurs.

This offers a major advantage for the operation of a restraint, because extra time would be obtained by the sensing computer triggering the system before the event. In an aviation environment and in particular an IBAHRS application, this operation of the system would ensure that the occupant is secured in the safest position before the impact has an inertial effect on him/her.

The most obvious use of such technology could be to monitor, for example, attitude, pitch, altitude, rate of descent, height above ground and condition of undercarriage, to determine a go/no-go state of the restraint system. Such monitoring equipment already exists in modern commercial aircraft, such as Doppler based systems. These types of system can detect accurate height above ground and rate of change of height and should form part of future developments in inflatable restraints.

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A Retrospective Analysis of Potential Airbag Benefit in U.S. Army Helicopter Crashes

Philip A. Johnson
John S. Crowley
B. Joseph McEntire
Nabih M. Alem
Frederick T. Brozoski

United States Army Aeromedical Research Laboratory
Fort Rucker, Alabama

ABSTRACT

Purpose: In 1993, Shanahan, Shannon, and Bruckhart conducted a review of U.S. Army helicopter accidents (1984-1992) and concluded that airbags could have saved 30 lives had they been installed across the Army fleet during the study period. This review was based on an ideal airbag system performing as designed within its design constraints (e.g., crash vector limits). In the case of the UH-60, this system would consist of 4 bags—two forward and two lateral. Recent manikin research at the U. S. Army Aeromedical Research Laboratory (USAARL) has suggested that certain lateral airbag designs may cause injury, so potential redesigns include a "front bag only" configuration. The purpose of this study is to update the Shanahan data and recalculate the benefit in the UH-60 based on a system using only forward airbags. **Methods:** The U.S. Army Safety Center (USASC) data were reviewed for UH-60 accidents in which a 4-bag or 2-bag system would have prevented serious injury, had it been installed. A team of flight surgeons and engineers made the judgements based on kinematic, injury mechanism, and anatomic criteria. **Results:** There were 48 Class A UH-60 mishaps occurring between 1980 and 1996, resulting in 32 cockpit fatalities. Using Shanahan's criteria, three fatally injured aviators were identified who would have survived if an ideal four-bag airbag system had been installed. Of these three "saves," one depended upon the presence of a lateral airbag. In addition, a fourth aviator was identified whose fatal facial injury would have been prevented by a frontal airbag, but his other severe injuries may have precluded survival. **Conclusions:** Based only on estimated fatalities prevented, a two-bag airbag system would have prevented three of the four fatalities prevented by a four-bag system. Additional benefits from the reduction of less severe injuries will be discussed. A more dramatic benefit might be expected in less crashworthy aircraft.

INTRODUCTION

The improvements in crashworthy design standards for helicopters over the last two decades have improved the prospects of survival in helicopter accidents in more modern airframes (Shanahan and Shanahan, 1989). Examples such as the UH-60 Blackhawk and the AH-64 Apache in the U.S. Army, and new designs such as the EH-101 Merlin and the

Eurocopter Tiger attack helicopter in Europe, embody energy attenuating mechanisms in undercarriage, body and seating to minimize the loads transmitted to the occupant during an impact.

The principles of these advances are now embodied in the Crash Survival Design Guide (Department of the Army, 1989) and are the result of research into accident patterns during the 1960s and 1970s. The embodiment of these features does not, however, address all possible injury mechanisms in the modern aircraft and does not affect the accident performance of older airframes at all.

In 1993, Shanahan, Shannon, and Bruckhart published a report estimating the potential benefit of fitting inflatable supplementary restraint devices (airbags) into existing aircraft in order to address the observed incidence of head and upper body injuries previously reported (Shanahan and Shanahan, 1989). The assumptions in the report (Shanahan, Shannon, and Bruckhart, 1993) included the airbag system design, since no helicopter airbag system had then been produced or tested. It was assumed for working purposes that an airbag system would have an enveloping, three bag design for tandem (fore and aft) cockpit helicopters and at least a two-bag (forward and lateral) system for the side-by-side cockpit aircraft. It was also assumed that any system would be fully effective in preventing the injuries that were potentially preventable by airbags.

This report and other work at the time (Alem et al., 1991) prompted decisions to investigate the fitting of airbags to existing airframes. The considerations of cost effectiveness and lifetime dictated that the initial investigations were made using the UH-60 Blackhawk as the subject aircraft, notwithstanding the fact that Shanahan's paper showed that the potential benefits in other aircraft could be greater. The importance of using a more modern aircraft with a longer service life is clear, and the principles determined in initial testing could be later applied to other aircraft.

The process of review during the development of the UH-60 airbag system showed that the lateral airbag was capable, under certain circumstances, of inflicting serious injury, specifically to the outboard arm of the front seat occupant. This finding prompted a number of potential redesign options for the system, including the possibility of removing the lateral airbag, either temporarily or permanently.

The requirement to reevaluate the previously determined effectiveness of a theoretical system followed from these findings, since the option of removing the lateral bag implies a reduction in overall effectiveness of the system.

METHODS

The original data from Shanahan's paper (Shanahan and Shanahan, 1989) were used, which consisted of information taken from the USASC's database. These data were individual injury records of aviators involved in accidents. Each record was identified by social security number, and more than one injury record may have belonged to one individual, indicating that the individual concerned suffered more than one injury.

The database contained a wide range of information about each recorded accident, including details of the accident kinematics, mechanical information about the aircraft, weather and injury data. All accidents classified as A through C were included in the database. The subsets of data, which we utilized in this study, were those relating to injury (location, causation, severity and survivability) and impact kinematics (defining how the impact was determined to have occurred).

Two separate analyses were performed. The first was to identify those cases that were categorized as potentially preventable fatalities in Shanahan's study, and to review these to estimate the relative effectiveness of a frontal airbag system. The second was to take a wider look at individual injuries and estimate the numbers and severity of single injuries that might be prevented by airbags.

All data were manipulated within an Excel® spreadsheet, utilizing the filtering facilities within this software package.

Assumptions

Throughout this study we have had to make some basic assumptions. The first of these was that we had no control over the contents of the USASC database, and relied upon the integrity of the output from this source. It should be stated that this source is heavily relied upon by many sources and that our level of confidence in content and retrieval is high.

Where projections are made regarding the outcome of an accident assuming the presence of airbags, no specific system is considered. The airbag system is presumed to be an ideally functioning and configured system.

Analysis of Fatalities

Data Set

The data set for the first analysis included all UH-60 accidents recorded in the USASC database between October 1980 and September 1996 as Class A accidents. Class A accidents are defined as those resulting in loss of life, total loss of an aircraft (whatever the value) or monetary cost of $1M or greater. The cases were further defined by a database categorization of survivable or partially survivable (i.e. accidents categorized as nonsurvivable were not included).

Analysis of Data

This resulted in a data set of 48 accidents, in which there were 32 cockpit fatalities. We applied Shanahan's original criteria to these cases by applying filters for the variables shown in Table 1.

Table 1.
Summary of injury criteria applied.

Database information	Criteria applied
Injury to	Head, Neck, Trunk (Chest, Abdomen), Upper Arm
Injury coded as	Fatal
Mechanism of injury	Struck against, Struck by, Caught in/under/between
Not caused by	Excessive G forces, Multiple injury producing mechanisms
Caused by	Chemical/thermal burns (included only if airbag preventable injuries restricted egress/escape. Not included if other fatal injuries present).

The resulting cases were then subjected to a further analysis of recorded data to simulate the presence of a frontal, but no lateral, airbag. The USASC database records the estimated impact characteristics estimated by the accident investigation team at the scene, using ground markings and damage to the aircraft. This information is recorded as longitudinal and vertical velocity, roll, pitch and yaw (Table 2).

Table 2.
Kinematic limits applied to represent frontal airbag area of influence.

Flight parameter	Criteria
Yaw	Between +30° (nose right) and –30° (nose left)
Pitch	Between –45° (nose low) and +120° (nose high)
Roll	Between +30° (roll right) and –30° (roll left)

These kinematic characteristics were considered to represent the envelope within which a frontal airbag might be expected to provide protection to the seat occupant.

Analysis of Injuries

Data Set

The data set for the second analysis included all of the recorded accidents involving UH-60 aircraft over the study period (October 1980 – September 1996). The cases included all class A to C (inclusive) accidents during this time.

We excluded all records that included blank lines as errors of data transcription. The printed records were reviewed to ensure that true accident cases were not rejected on this basis. This resulted in a data set including 72 accidents and 1196 individual injury records. It should be noted that a single occupant might have suffered a number of recorded injuries.

All individual records that related to crew positions other than right or left cockpit seat were then excluded because airbags are only to be fitted into pilot positions. This reduced the number of accidents to 69, with 458 individual injury records.

Analysis of Data

We took the set of injury records and progressively filtered them to determine which accidents and individual injury cases could be categorized as being preventable utilizing an airbag system. The filters were applied to control accident kinematics, injury location, type of injury and injury severity.

Kinematics

These parameters were applied to exclude accidents in which the airbag system could not reasonably be expected to protect the occupants against the forces involved or cases in which the direction of forces indicated that an airbag system would not be effective:

$0 \text{ ft s}^{-1} <$ Vertical speed <85 ft s (Shanahan and Shanahan, 1989) -- to avoid including ground accidents (such as hit by another aircraft), in which airbags would not deploy, and to exclude excessive forces as above.

Ground Speed < 90 kt -- to exclude excessive forces

$-45^\circ <$ Pitch $< 90^\circ$
$-30^\circ <$ Roll $< +30^\circ$

Pitch and roll parameters were intended to exclude cases where an airbag system would not have protected the occupant because the principle directions of forces in the accident were outside the areas of deployment of the airbags.

Accidents that were coded as including "loss of occupiable space" were excluded because airbags cannot be expected to protect in this situation.

Injury Location

We examined the location of the injury as coded in the database by body region to exclude any injuries that were caused to parts of the body that are outside the area possibly protected by airbags. Injuries to the head, trunk (thorax, abdomen), and arms were included; injuries to all other regions were rejected.

Type of Injury

The database includes codes for the type of injury in terms of "mechanism of injury." We included injuries that were coded as being caused by a mechanism of "struck by" or "struck against," but excluded those that were coded as "caught in/under/between." We included injuries that were recorded as being "struck against/by," "exposed to," or

"experienced," but excluded those injuries categorized as being due to "excessive G forces" or "multiple injury producing mechanisms."

Injury Severity

We included all classifications of injury severity from minor to fatal in this analysis. Each injury has been treated as a separate entity, and at this stage, no attempt has been made to relate individual injuries in a particular accident.

We examined the cases remaining after this filtering process and were able to categorize the individual injuries into three groups depending upon the likelihood of an airbag system preventing or ameliorating the injury suffered. The results were divided into three groups (Table 3).

Table 3.
Characteristics of injury groups determined.

Group	Characteristics
0	Injury not preventable by airbags
1	Preventable injury in airbag area which could have been prevented by airbag system
2	Injury in airbag area, but may not be preventable

These groups were then further analyzed to determine injury severity within each category, producing a breakdown of severity of injury compared with predicted airbag effectiveness (Table 4).

This outline of the projected effectiveness of airbags against single injuries, as previously stated, does not account for multiple injuries in individuals. We therefore decided to further analyze the results to determine the number of individuals with more than one injury, and to break these down by number and severity of prevented injuries for casualties.

Finally we examined the injuries categorized as fatal or critical, and determined in which cases all of these injuries could be regarded as preventable using airbags.

RESULTS

Analysis of Fatalities

Using the criteria outlined above we identified three cases in which a fatality was considered to have injuries leading to death that were potentially preventable with the presumed "perfect" airbag system. One further case involved injuries which were

categorized as fatal, but which were preventable with an airbag system. This individual had other injuries which would not have been prevented by an airbag system and may have been fatal in isolation.

This provided a comparison with the four cases which Shanahan identified, and the further (yaw and kinematic) criteria were applied to these cases.

We found one case in which the aircraft impacted the ground with 70° of right roll. We concluded that any benefit that might have been available from an air bag system in this accident would have come from the lateral bag; therefore, this case was removed from the list of potential saves.

Analysis of Injuries

The results of the analysis of injuries by potential for prevention by airbags and severity of injury are presented in Table 4. When reading these results it should be noted that the sample size of the "critical" group was very small.

Table 4.
Analysis of injuries by preventable category.

		Preventable category (see Table 3)		
Injury category	Total	0	1	2
Fatal	13	6	5	2
Critical	3	1	2	0
Major	70	45	18	7
Minor	81	41	36	4
Minimal	57	32	22	3

These figures may be presented as a percentage of injuries that may be prevented by an airbag system. This produces the results shown in Table 5

Table 5.
Preventable injury as a percentage by category.

	Preventable category (see Table 3)		
Injury Category	1 (%)	2 (%)	1 + 2 (%)
Fatal	38	15	53
Critical	66	-	66
Major	26	10	36
Minor	44	5	49
Minimal	39	5	44
Total	213	35	248
Mean	42.6	7	49.6

Multiple Injury Cases

We identified 50 cases in the sample in which more than one injury was present. These are represented in Figure 1. Injuries were found not to be preventable in only 22% of these cases, with some injuries preventable in 70%. All of the injuries were considered to be preventable in only 8% of cases.

We found that in 18 of the 50 cases, the most serious or disabling injury was preventable with airbags. This group included cases where the most serious injury was coded as minor, and included cases where a major or fatal injury was found to be preventable, but other major or fatal injuries existed.

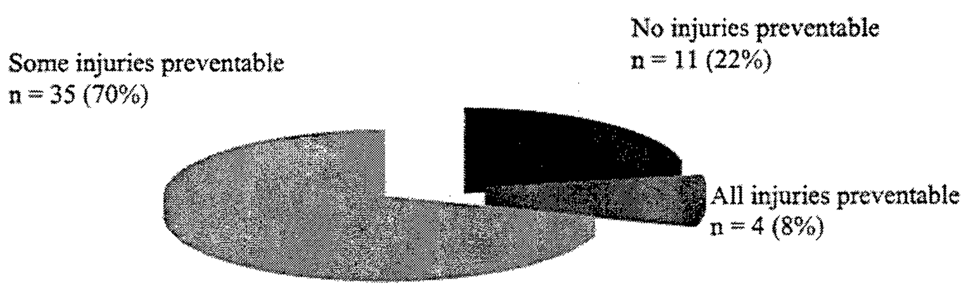

Figure 1. Preventable injuries in cases of multiple injury.

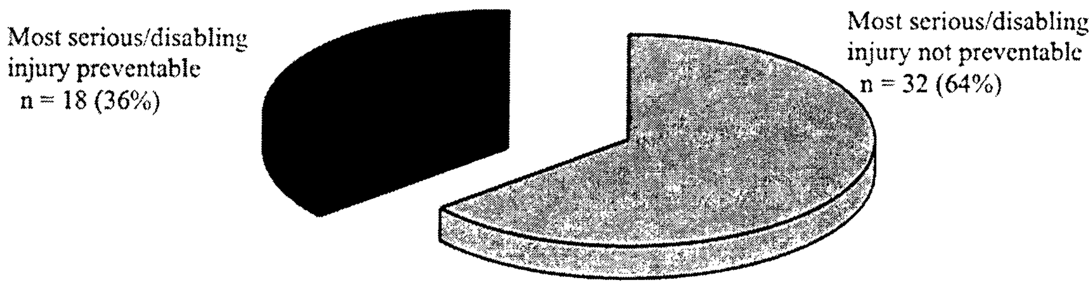

Figure 2. Most serious/disabling injury preventable.

We examined the figures for all injuries classified as major or greater severity, and found that 6 subjects with injuries classified as major or greater had all of their injuries determined as being preventable, while 17 had some of these injuries in the preventable category.

DISCUSSION

In this study, we have looked at two separate situations, using the same original data set. In the initial part of the study, we found that reexamining the data to estimate the projected effectiveness of a frontal airbag only system suggests that the majority of fatalities preventable with a full system would still be helped by the frontal bag only system. In a small sample group (only four "saves" were recorded in the original paper), we showed that 75% of the "saves" from a full system would be considered saves with the more limited airbags.

This result was not unexpected when the predominant characteristics of helicopter impacts were considered. The major components of helicopter impacts are forward and down, with a smaller number exhibiting yaw or rotation at impact.

In the second part of the study we took a rather different approach to the data by looking at the projected effect of the airbag system on individual injuries, rather than complete cases. The logical argument behind this approach is that while it is very useful to examine complete cases to ascertain how many aviators lives might have been saved if airbags had been in use, the benefit of fitting airbags is not only to be measured in lives saved, but also in injuries prevented. We believe that this gives a different, but relevant, perspective to the discussion over the potential benefits of fitting cockpit airbags to helicopters.

We found that a high proportion of injuries (even up to 50%) of all severities might be prevented by a fully effective airbag system. We were not surprised to find that as combinations of injuries increase, so the proportion of cases with all injuries prevented decreases. This is quite understandable, and perhaps explains why earlier research has produced what appear to be relatively low estimates of cases where all injuries might be prevented.

The argument that injuries are caused by repeatable mechanisms, and therefore tend to occur in consistent patterns, is a valid one, but it has to be countered by the assertion that in employing airbags, the aim is to improve survivability and outcome for aviators in accidents. If airbags can be shown to decrease the incidence of injuries of all severities over a range of accident parameters, it should follow that the overall outcome for occupants will be improved with a fully functional airbag system.

CONCLUSIONS

We conclude from the first part of the study that an airbag system utilizing only a front bag is less effective than a full (front and side) system, but that it will prevent the majority of fatalities that have been previously predicted for a full system.

The second part of the study leads us to conclude that airbags may be expected to remove or reduce a large proportion of injuries of all severities, and that effective airbag systems remain a worthwhile addition to other crashworthy features in current and future helicopters.

The opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the U.S. Army and/or the Department of Defense.

DISCLAIMER

The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Citation of trade names in this report does not constitute and official Department of the Army endorsement or approval of the use of such commercial items.

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Crashworthiness and Inflatable Devices in British Army Air Corps Helicopter Accidents

Colonel MG Braithwaite OBE L/RAMC
Consultant Adviser in Aviation Medicine (Army)
Headquarters Director Army Aviation, Middle Wallop, Hampshire, UK.

Although there may be theoretical advantages to enhancing crashworthiness through inflatable devices in the aircraft cockpit, will they really affect the outcome of survivable mishaps? It is difficult to be prospective, but we can look back at the accidents and assess whether air bags or inflatable restraint mechanisms would have made any difference.

This short review comprises a discussion of the crashworthiness of British Army Air Corps (AAC) helicopters derived from a review of accidents over the past 2 decades. The mishaps were then reviewed to consider the advantages that may have been gained had inflatable devices been incorporated.

The essence of crashworthiness is to enhance the survivability from aircraft accidents by minimising the exposure to damaging impact forces. Its aim is to prevent incapacitating injury so that escape from the accident and events following it can be effected, and the future health and performance of personnel are not compromised.

Energy Attenuation of Aircraft Structures and Maintenance of the Occupant Space

Neither of the AAC's current operational aircraft, the Gazelle and Lynx, was designed with particular reference to crashworthiness. The Lynx airframe has a greater structural strength than the Gazelle and so is able to withstand greater impact forces before the survival of the occupants is compromised. However, the Gazelle cabin is considerably more fragile and often disintegrates at force levels which can otherwise be tolerated by the human body. Survival from a Gazelle crash is therefore often a matter of chance and depends largely on whether the crew escape catastrophic random injury. Although on occasions, accident reports have commented that the design of the Gazelle causes it to crumple and so minimise injuries, this cannot be regarded as a design feature but merely a fortuitous tendency. In particular, the Gazelle undercarriage was not designed as a deformable or crashworthy structure, although it has behaved in a propitious manner by splaying and collapsing, thus attenuating +Gz forces to a certain extent. This tendency is only of benefit if the undercarriage supports do not penetrate the cockpit.

SEATING

If energy is not attenuated sufficiently by the aircraft structure, dangerous levels of impact acceleration may be transmitted to the occupants via their seats. No AAC helicopter crew or passenger seat is of crashworthy design. In a Gazelle crash with a high +Gz impact component, the forces can even be amplified through dynamic overshoot

because of the short distance between the cabin floor and the seat pan. This phenomenon has also been seen in Lynx when the vibration isolator springs on the seat mountings were compressed as a result of the force. The seats are to be modified to prevent this tendency. As well as +Gz forces, any significant -Gx acceleration will displace the crew seats from their mountings. This propensity has been more common in Gazelle accidents, where the retention or displacement of seats has been a variable and unpredictable feature not related to impact forces.

Passengers sitting on the Lynx cabin troop seat are particularly poorly protected against impact forces. In two accidents since 1982, fatalities or an increased severity of injury were attributed in part to the deficiencies of this seat. Furthermore, passengers carried on the clear floor of the Lynx must rely only on deformation of the airframe to protect them against impact acceleration. The frequency of spinal injury in this series of accidents must be attributed, at least in part, to the poor energy attenuation of all aircraft seats.

Retrofitting crashworthy crew seats is unlikely to be sanctioned. However, because of the major deficiencies of the Lynx troop seat, the Lynx Survivability Study recommended research into replacing this seat, and this study is ongoing. As unacceptable risks are now being imposed on passengers, and hence the duty of care is being neglected, the development and procurement of an improved Lynx troop seat must be achieved as soon as possible.

RESTRAINT

It is well established that the restraint of helicopter occupants should be effective not only to enhance protection from primary impact but also to prevent injury from secondary collisions against cabin structures. Although the material of restraint harnesses is of high quality and rarely fails, several aspects of restraint in AAC helicopters have caused concern in this series of accidents. The topic will be approached by considering the following issues:

- restraint of front seat aircrew.
- passenger restraint

Restraint of Front Seat Aircrew

A 5-point harness with a lockable inertia reel mechanism is fined to all current AAC helicopters, and the GQ quick release box (QRB) is standard throughout the present fleet There has only been one case of the negative G mounting of the harness failing. Generally, injuries have been prevented or minimised by this efficient restraint system, as long as it has been properly used. In one fatal accident, a front seat crewman's lap strap lug was not inserted into the QRB. This was an accident with substantial +Gz forces in which both crew perished in the post-crash fire. The crewman's ineffective restraint was considered to have possibly contributed to his post-impact incapacitation.

Passenger Restraint

Lynx and Gazelle helicopters have 3-point lap and diagonal rear passenger restraint harnesses. In 8 accidents in this series: four Gazelle and four Lynx, comments were made about the provision and/or performance of passenger restraint.

Gazelle: In three of the four Gazelle accidents, the passenger harness mounting was torn from the floor. On all occasions, the severity of injury to the passenger was probably increased because of this failure. In the fourth accident, as the passenger was wearing a webbing belt and pouches, it was difficult to tighten the harness and he submarined" under the lap strap. Whilst it would he difficult to strengthen the passenger harness mounting points on Gazelle, the latter problem could have been prevented by the passenger removing his webbing before adjusting his harness, and this should be part of the standard passenger brief.

Lynx: Three of the four Lynx accidents involved carrying troops in the rear cabin: two were operational sorties, and the third was a familiarisation flight for cadets. In each case, some or all of the personnel were unrestrained, and in two of the accidents death or serious injury was a direct result of the absence of restraint. Had they been, it is considered likely that some deaths may have been prevented and/or less severe injury caused. The situation with regard to troops on operations has other considerations. Soldiers who are inserted by helicopter into field locations on internal security operations carry their weapons and personal equipment. They are required to deploy immediately on landing so that the aircraft is exposed to the potential hostile threat for as short a time as possible. Because of the bulk of a soldier and his equipment, it is difficult or impossible to fit, adjust and release the Lynx troop seat restraint harnesses. Personnel are therefore either carried on the seat without restraint, or on the clear cabin floor. A method of restraining troops seated on the clear floor has been devised and was recommended as a short-term solution pending the development of a new seat. However, this solution was not accepted by operating units and is not practised.

POST CRASH FACTORS

Survival of the occupants of aircraft accidents also depends on the nature of events that occur after the accident. This subsection wilt address the following issues:

- post-crash fire
- emergency egress rescue

Post - Crash Fire (PCF): In this series there have been six accidents (four Lynx, two Gazelle) when the aircraft has burned after the crash. Fire has been directly responsible for three fatalities. Some modifications to reduce the chance of PCF in Lynx have been recommended by the Lynx Survivability Study and other measures are under review. Although probably expensive, further implementation of the recommendations of this study is urgently required. It is unlikely that further improvement can be made to the

Gazelle, but this most important crashworthy feature should be applied to all future helicopters.

Emergency Egress: Of the 53 survivable flying accidents, there were nine in which difficulty in egress from the aircraft was experienced. The reasons were equally distributed between incapacitating injury, entrapment, and jammed or blocked emergency exits. All may be attributed to the poor energy absorption of current AAC helicopters.

Would Air Bags or Inflatable Restraint Have Reduced the Number of Fatalities/Injuries?

The function of air bags is primarily to prevent injury as a result of primary or secondary impact of the body with cockpit structures. Inflatable restraints 'improve" the characteristics of the restraint system and further distribute the load on the body primarily during -Gx impacts.
The accidents in this series were subjected to a personal review to determine the degree of benefit from these devices. The "gains" are shown below:

Gains From Fitting an Air Bag.

Lynx	Gazelle	
2	1	front seat fatalities (footwell in Lx)
1	9	front seat major injuries
	1	front seat minor injuries
7		rear seat major injuries
1	12	rear seat minor injuries

Gains From Fitting Inflatable Restraints.

Lynx	Gazelle	
2	1	front seat fatalities
1	6	front seat major injuries
1	2	front seat minor injuries
	3	rear seat major injuries
	5	rear seat minor injuries

CONCLUSION

In conclusion, had an inflatable device been fitted in Lynx **and** Gazelle, several lives and injuries may have been prevented over the last 16 years. As we learn more and more about crash dynamics, There is no doubt that all future helicopters should have the best safety features fitted at the time of manufacture, if only to comply with BEST

PRACTICE based on available knowledge at the time. However, from the limited British Army experience in aircraft that are NOT inherently crashworthy, there is not overwhelming evidence that it is justifiable that inflatable devices are retrofitted to the current fleet. The British AAC look forward to introducing our first CRASHWORTHY aircraft – the WAH-64 (Apache) in the near future and perhaps applying the same principles to this worthy airframe.

AH-64 Injury Reduction Potential with Cockpit Airbags and Optical Relay Tube Removal

B. Joseph McEntire and Samuel G. Shannon
U.S. Army Aeromedical Research Laboratory
Fort Rucker, AL

Christopher Smith (MAJ) and George Crockatt
U.S. Army Safety Center
Fort Rucker, AL

ABSTRACT

US Army AH-64A Apache helicopter pilot and copilot injury data and injury-producing mechanisms were analyzed to determine injury mitigation effectiveness if the copilot/gunner (CPG) optical relay tube (ORT) was removed or if a cockpit airbag system was installed. This required that each accident file be individually reviewed. A total of 49 AH-64 aircraft were involved in Class A and B mishaps between 1 Oct 1983 and 30 September 1992. Of these, 17 were discarded since they were either catstrophic (n=4), consumbed by fire (6), or not considered applicable (7) since airbag deployment criteria were not met and/or injuires were not received. For the ORT removal option, no reduction in rear seat occupants injuries was predicted. A reduction of 11.7 percent of the 111 injuries received by the front seat occupants could have resulted. With installation of a cockpit airbag system, injury reductions resulted for both crew stations. Overall, 34.2 percent of the 111 injuries received by the front seat occupants could have been prevented or reduced in severity with an airbag system installed. In comparison, 43.2 percent of the 95 injuries received by the rear seat occupants could have either been prevented or reduced in severity with an airbag system installed. It was predicted that removal of the ORT structure would be effective in mitigating CPG head injuries, but not in reducing overall injury severity. The airbag was predicted to mitigate injuries and reduce overall injury severity.

INTRODUCTION

There is an operational requirement for a supplemental aircrew member restraint system which will protect aviators in potentially survivable aircraft accidents[1]. Several reviews have identified the prevalence of contact induced head and upper torso injuries in Army helicopter mishaps[2,3]. Approximately two-thirds of the major and fatal injuries in potentially survivable mishaps are attributed to head and upper torso strikes to cockpit structure[4]. Contact injuries may result when collapsing structure encroaches occupied areas, but are more frequently the result of the occupant flailing, or a combination of the two.

According to a study conducted by the U.S. Army Aeromedical Research Laboratory on Army helicopter mishaps occurring from 1 October 1983 through 30 September 1992[5], there were 282 Army class A and B accidents in 6 different helicopter types. The crashes resulted in 128 fatalities, 26 aviators with disabling injuries, and 176 injuries sufficient to require hospitalization or days away from work. Estimated cost of these deaths and injuries amounted to over $150 million. Assuming mishap rates and severity remain relatively constant over time, the threat of potential injury to aircrew members is great. Another work addressing this problem is AH-64 Crash Kinematics[6]. That work documented the injuries and injury severity produced in AH-64 accidents and the aircraft's mishap kinematic parameters. This was used as a baseline for injury expectation in this analysis.

The cockpit airbag system (CABS) is supposed to reduce the potential injury severity by reducing the crewmembers' strike envelope during primary and secondary impacts[7]. Airbags assist in proper positioning of the aviator for improved tolerance to crash impacts by encapsulating him/her in a protective air cushion similar to those used in automobiles. The potential effectiveness of airbags for injury reduction has been demonstrated in attack type helicopter crew stations[8].

The AH-64 Apache aircraft is an anti-armor, attack helicopter. The aircraft copilot/gunner (CPG) is positioned in the forward cockpit and utilizes an optical relay tube (ORT) for identification and designation of potential targets. The ORT is a mechanical structure positioned in

front of the CPG and creates a mishap strike hazard. The ORT has been identified as an injury causing item in AH-64 mishaps[8].

The purpose of this investigation was to quantify the injury reduction potential of a CABS equipped AH-64 Apache aircraft versus AH-64 aircraft with the ORT removed. The ORT was suspected of being a primary strike hazard for the front seat occupants.

METHODOLOGY

Study Population

It was first necessary to gain a study population of accidents involving injuries. A particular subset of that group was strike injuries incurred as a result of crash deceleration (g) forces experienced during an aircraft accident. The U.S. Army Safety Center database was queried to produce accident cases where strike injuries and/or g forces associated with impact were recorded since 1985 (the first AH-64 strike injury producing accident was in 1985). The initial study population consisted of 48 accident cases involving 49 aircraft. These mishaps were classified as either A or B[9]. Table 1 provides the thresholds for these two classifications. Thirty-nine accidents were classified as Class A and 9 were Class B.

Table 1. Department of Army Regulation 385-40, Aviation Mishap Classification.

Mishap class	Total property damage	Injury level
A	Greater than $1,000,000	Fatality or permanent total disability
B	Between $1,000,000 and $200,000	A single permanent partial disability or five or more personnel require inpatient hospitalization

The population was then screened to identify accident cases that had potentially preventable strike injuries. This process eliminated 17 accident cases from the population. Four were eliminated because of the catastrophic nature of the mishap, i.e., nothing could be done to protect the occupants from injury after accident sequence onset. An example of this type of accident is an aircraft encountering high tension wires several hundred feet high and tumbling out of control to ground impact. Impact forces were excessive and were well past the point of human endurance or design consideration. Seven mishaps were considered not applicable and removed from the study population. These accidents were where the g forces encountered on impact were deemed to be of insufficient severity to cause activation of the airbag systems. The thresholds used in this study are provided in Table 2. The other six accident cases were eliminated since the injuries occurred during egress. The study population containing potentially preventable strike injuries then became 31 accident cases involving 32 aircraft, 26 Class A and 5 Class B.

Table 2. Airbag activation criteria.

Direction	Acceleration (g)
Vertical	8
Forward	4
Rearward	10
Sideward	2

Injury Mitigation

For all accidents, each reported injury was examined by crew position, body region, severity, and injury producing mechanism. The major body regions were head, neck, spine, torso, upper extremities, and lower extremities. The injury severity categories were fatal, critical, major, minor, and minimal. The category "prevented" was created to track which injuries were predicted to be prevented. The injury producing mechanism qualifiers were used to help determine whether the injury would be mitigated with the ORT structure removed or with the CABS installed.

Each injury was assessed for mitigation potential by considering its type, mechanism, mishap kinematics, and cockpit structural integrity as reported in the accident cases[10]. Example injury types and mechanisms are listed in Table 3, and example kinematic and structural parameters are listed in Table 4. Once these variables were identified for each injury and an understanding of the individual's crash environment established, a prediction was made on whether the injury could have been mitigated if the ORT were removed or CABS installed. Agreement among authors was required for the mitigation decision to be accepted.

To aid determination of injury mitigation, occupant forward and lateral flail envelopes for 5-point restraint systems[11] were considered with anticipated airbag deployment zones[7]. The flail envelopes and airbag deployment zones are illustrated in Figures 1, 2 and 3.

Table 3. Example injury types and mechanisms.

Injury type	Mechanism action	Mechanism qualifier
burns	caught	aircraft
dismemberment	in	aircraft fire
amputation	under	armor
avulsions	between	ceiling
decapitation	experienced	collective
fractures	exposed to	console
chip/wedge	struck against	cyclic
compound	struck by	door
compression	thrown from	excessive (deceleration forces)
crushed		external objects
incomplete		floor
stress injuries		gunsight
dislocation		instrument panel
strain		main rotor
sprain		seat
wounds		structure
abrasions		windshield
contusion		night vision device
laceration		transmission
puncture		
transection		

Table 4. Example kinematic and structural parameters.

Kinematic	Structural
forward velocity	roof
downward velocity	left side
pitch angle	right side
roll angle	nose
yaw angle	floor
roll over	seat stroke
multiple impacts	
vertical G's	
longitudinal G's	
lateral G's	
flight path	
obstacles	
impact angle	

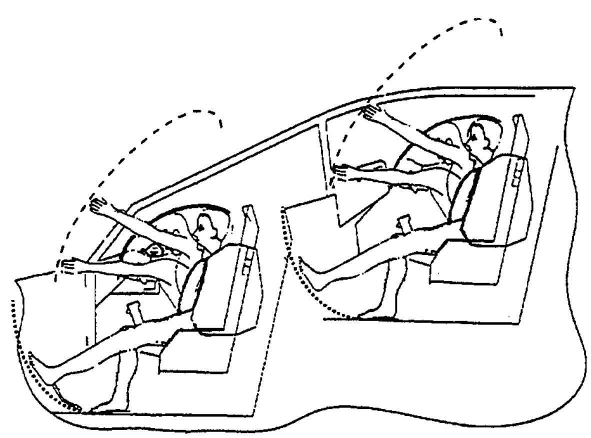

Figure 1. Occupant forward flail envelope.

Increase accident severity

The last area examined was a determination if CABS deployment would increase the severity of the accidents in the population or induce injury. Under certain circumstances, it was determined that, if multiple ground contacts occur, the CABS may deploy and restrict the aircrews' ability to maintain aircraft control after the initial impact, presumably increasing the severity of the accident, possibly even destroying the aircraft.

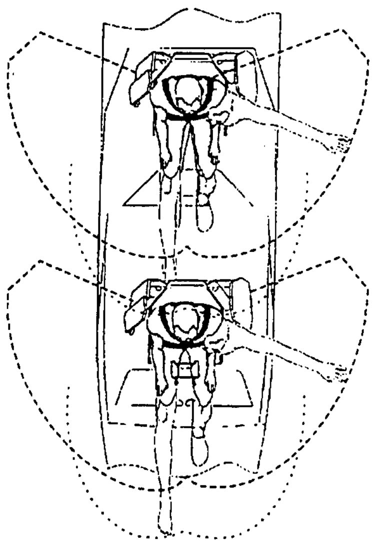

Figure 2. Occupant lateral flail envelope.

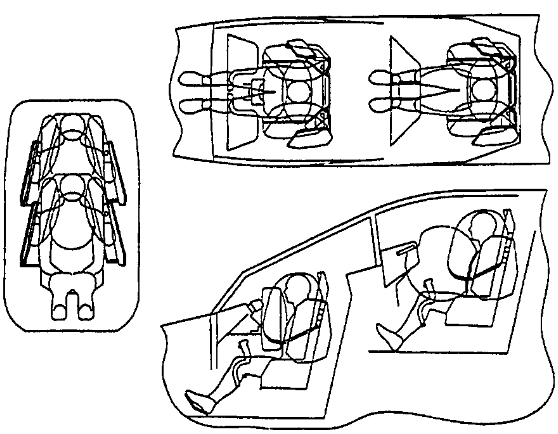

Figure 3. Airbag deployment zones.

RESULTS

Injury

The CPG occupants incurred 111 injuries, while pilots incurred 96. The distribution of these injuries are provided in Table 5. The head was the most frequently injured region followed by the torso, lower extremities, and upper extremities for both crew stations. No differentiation was made between the severity of these injuries or the number of injuries an occupant may have received to a particular body region.

Table 5. Total injury distribution.

Body region	CPG n	CPG %	pilot n	pilot %	combined n	combined %
General	2	1.8	1	1.0	3	1.4
Head	34	30.6	27	28.4	61	29.6
Lower ext	24	21.6	22	23.1	46	22.3
Neck	6	5.4	6	6.3	12	5.8
Torso	26	23.4	26	27.4	52	25.2
Upper ext.	19	17.1	13	13.6	32	15.5
Total	111		95		206	

The body regions with injuries predicted to be most frequently mitigated were the head, torso, and upper extremities. The lower extremities did not have any injury mitigation with either CABS installed OR the ORT removed. The distribution of injury severity for each of these body regions are provided in Tables 6, 7, 8, and 9 along with the predicted distribution of injury severity based on ORT removal and CABS installation.

Table 6. Head injury reduction.

Injury severity	CPG Actual n	CPG ORT removed	CPG CABS installed	Pilot Actual n	Pilot CABS installed
Fatal	1	1	1	1	0
Critical	2	2	2	1	0
Major	9	6	4	5	0
Minor	13	8	5	13	4
Minimal	9	5	10	7	6
Total	34	22	22	27	10
prevented		12	12		18

For the head body region in Table 6, both ORT removal and CABS installation resulted in the prevention of 12 CPG injuries. Neither prevented the fatal or critical head injuries. Airbags were predicted to reduce a greater number of major and minor head injuries. The slight reduction of minimal head injuries for airbags is the result of predicting some major and minor injuries to be reduced to the minimal level and not prevented entirely. It was assumed that contusions and abrasions to the face may

result from airbag deployment, thereby still being counted as a minimal injury. For the pilot position, the airbag would have prevented the one fatal, one critical, and all six major injuries.

As shown in Tables 7 and 8, the airbag was predicted to provide reduction to the major and minor injuries for both the pilot and CPG positions. ORT removal would have only prevented one minimal upper extremity injury. This injury was an arm flail against the ORT structure.

Table 7. Torso injury reduction.

Injury severity	CPG Actual n	CPG ORT removed	CPG CABS installed	Pilot Actual n	Pilot CABS installed
Fatal	3	3	3	0	0
Critical	2	2	2	0	0
Major	8	8	5	4	1
Minor	6	6	4	7	4
Minimal	7	7	9	15	17
Total	26	26	23	26	23
prevented		0	3		3

Table 8. Upper extremities injury reduction.

Injury severity	CPG Actual n	CPG ORT removed	CPG CABS installed	Pilot Actual n	Pilot CABS installed
Fatal					
Critical					
Major	3	3	2	1	1
Minor	4	4	1	3	1
Minimal	12	11	3	9	3
Total	19	18	6	13	5
prevented		1	13		8

No injury reduction to the lower extremities was predicted, as shown in Table 9. For the two remaining body regions, general and neck, ORT removal was not predicted to reduce any injury severity, while the CABS was predicted to reduce two minor neck injuries to a minimal and a prevented injury.

The previous tables illustrate the predicted reduction of injury by major body region. What they do not clearly depict is how the injuries are redistributed to lower severities. This redistribution is depicted in Tables 10, 11, and 12 by crew position and prevention technique. These tables are intended to be read by finding the injury severity in the first column and the total injuries received at that severity in the second column, then reading across the column along the row to see how those injuries were distributed.

Table 9. Lower extremities injury reduction.

Injury severity	CPG Actual n	CPG ORT removed	CPG CABS installed	Pilot Actual n	Pilot CABS installed
Fatal					
Critical					
Major	5	5	5	3	3
Minor	9	9	9	4	4
Minimal	10	10	10	15	15
Total	24	24	24	22	22
prevented		0	0		0

Table 10 provides the redistribution for the CPG position if the ORT were removed. It illustrates ORT removal would not have distributed any injuries, but would have prevented 13. The CABS was more successful in the CPG crew station by redistributing the injuries to lower severity and preventing 30 from occurring. The pilot crew station CABS would also have prevented 31 injuries, including the one fatal and one critical injury.

Table 10. CPG injury redistribution with ORT removed.

Severity	n	fatal	critical	major	minor	minimal	prevented
Fatal	5	5					
Critical			4				
Major	25			22			3
Minor	37				32		5
Minimal	40					35	5
Total	111	5	4	22	32	35	13

Table 11. CPG injury redistribution with CABS installed.

Severity	n	fatal	critical	major	minor	minimal	prevented
Fatal	5	5					
Critical	4		4				
Major	25			16		3	6
Minor	37				21	5	11
Minimal	40					27	13
Total	111	5	4	16	21	35	30

Table 12. Pilot injury redistribution with CABS installed.

Severity	n	fatal	critical	major	minor	minimal	prevented
Fatal	1						1
Critical	1						1
Major	13			5		3	5
Minor	31				14	8	9
Minimal	49					35	14
Total	95	0	0	5	14	46	30

The number and percentage of prevented injuries are provided in Tables 13 and 14 by severity. For the CPG station, ORT removal is effective at preventing 11.7 percent of the injuries. The addition of CABS would more than double this number (27.0 percent) by preventing more injuries for the CPG position. Yet neither approach would have prevented the fatal and critical injuries. For the pilot position, the CABS provided slightly greater preventions (31.6 percent) than the CPG position, and it would have prevented the one fatal and one critical injury.

Table 13. CPG injury severity reduction.

Severity	n	ORT removed		CABS added	
		prevented	%	prevented	%
Fatal	5	0	0	0	0
Critical	4	0	0	0	0
Major	25	3	12.0	6	24.0
Minor	37	5	13.5	11	29.7
Minimal	40	5	12.5	13	32.5
Total	111	13	11.7	30	27.0

Table 14. Pilot injury severity reduction.

Severity	n	CABS added	
		prevented	%
Fatal	1	1	100
Critical	1	1	100
Major	13	5	38.5
Minor	31	9	29.0
Minimal	49	14	28.6
Total	95	30	31.6

Increased accident severity

Review of the accident cases revealed one mishap which could have resulted in an increased severity. While performing a banking maneuver, the aircraft developed an excessive sink rate and impacted the ground at 50 knots with a 25 degree left roll. The aircraft rebounded into the air and the pilot was able to regain control of the aircraft and perform a run-on landing 373 feet from the initial point of impact. The impact was estimated at 10.5 g. This level is in excess of the fire criteria used in this study and would have activated airbag deployment. The ability of an individual to overcome a combined ground strike and airbag activation to regain aircraft control and perform a run-on landing was deemed unlikely and would likely have increased the mishap severity.

DISCUSSION

It is clear that the CPG position injury reduction is limited to the low severity injuries, while the pilot position enjoys an injury reduction across the entire severity range. These results were surprising because the CPG position was expected to benefit most from the CABS. The reason for the effectiveness dichotomy became apparent when the individual accident cases were considered. The CPG position in the AH-64A is not as structurally sound as the pilot position. When there is a severe accident, the CPG position is frequently destroyed -- the occupant expires from loss of occupiable living space, which CABS cannot prevent. The pilot position, however, usually retains its structural integrity, even in the worst accidents. The one pilot fatality remaining in the study was from a glare shield strike that CABS would have easily prevented.

This trend continued even when we reconsidered the catastrophic accidents discarded in the first steps. The pattern emerged that strike injuries are not the primary

causes of mortality of either position. Rather, the primary mortality producing mechanism of the CPG position was loss of occupiable living space, while the primary mortality producing mechanism of the pilot position was excessive g forces.

Combining the effects of ORT removal and CABS installation were considered for the CPG position. The results of the combined effort were identical to the CABS CPG installation, and were deemed redundant to report.

The last area examined was CABS potential to increase the severity of any of the accidents in the population. This was assessed by determining if CABS activation would have occurred during a minor impact, preventing the aircrew from recovering the aircraft to landing safely. Inadvertent airbag deployments have been conducted in an AH-64 flight simulator[6]. None of the flight simulator test subjects lost control of the aircraft, but they were not in crash situations when the airbags deployed. Additionally, the bag designs and inflation pressure profiles proposed for the AH-64 aircraft are different from those evaluated in the simulator. This implies that the pilot reactions and flight abilities observed in the flight simulations may not be representative to similar events with the final CABS design. Under certain circumstances, it was determined that for multiple ground contacts, the CABS may deploy and retard the aircrew's ability to maintain aircraft control after the initial impact, thereby increasing the severity of the accident. This event could result in destroying the aircraft. Increased injury severity due to increased accident severity was impossible to predict.

Also considered was an increased possibility of facial injury when aircrew wear night vision goggles or helmet mounted displays. The concern is the possibility of forcing a helmet mounted device into the aircrew member's face by the CABS deployment. Again, this was difficult to predict.

This analysis was conducted in 1997 in response to a question on the benefit provided by an airbag restraint system in the AH-64 Apache if the optical relay tube (ORT) were removed. This analysis was performed with the literal assumption that "ORT removal" implied the gunner's crewstation (front seat) would be configured nearly identically to the pilot's crewstation (rear seat) in terms of stike hazards. Subsequent to this analysis, the ORT has been redesigned, but not removed from the AH-64D Apache LongBow helicopter. The redesign consists of shortening the ORT (moving it away from the occupant), but increasing it's projected contact area by adding a flat panel display. The net effect of our incorrect assumption is that the injury reduction estimated for an "ORT removal" is more generous that an "ORT redesign". Results of this analysis indicate a higher injury reduction benefit would be realized with an airbag system versus the "ORT removed". Therefore, it can be concluded that since the strike hazard of a redesigned ORT is greater than no ORT, the airbag benefit would be even greater.

CONCLUSIONS

For the CPG position, neither ORT removal nor CABS offered reduction in fatal or critical injuries. Twelve percent major, 13.5 percent minor, and 12.5 percent minimal injuries (11.7 percent of 111) could have been prevented with ORT removal. Twenty-four percent major, 29.7 percent minor, and 32.5 percent minimal injuries could have been prevented (27.0 percent overall) CABS. No difference was observed between CABS with ORT versus CABS without ORT.

For the pilot crew station with CABS, one fatal and one critical injury could have been prevented. The results show that 38.5 percent major, 29.0 percent minor and 28.6 percent minimal injuries could have been prevented (31.6 percent overall).

It was shown that removal of the ORT structure is effective at mitigating CPG head injuries, but not in reducing their overall injury severity. The airbag was determined to be effective at mitigating injuries and reducing overall injury severity.

Caution should be exercised when extrapolating these results to other airframes due to variances in structural response and energy attenuation capabilities. AH-64 accidents are survivable to a point, then rapidly become nonsurvivable, with different mortality producing mechanisms predominating in each crew position.

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Appendix A
Attendees at Workshop: Inflatable Restraints in Aviation

Nabih Alem
Research Biomedical Engineer
USAARL
Building 6901
Fort Rucker, AL 36362
Tel: (334) 255-6892
nabih.alem@se.amedd.army.mil

Xavier Avula
University of Missouri-Rolla
AFRL/HEPA
2800 Q Street
Wright-Patterson, OH 45433-7947
xavier.avula@he.wpafb.af.mil

Aljunda Bachar
Manager
TNO-MADYMO
21800 Haggerty Suite 305
Northville, MI 48310
Tel: (248) 449-1755
Fax: (248) 449-7574
aljundi@madymo.com

Lindley Bark
MSC Software Corporation
4939 W. Ray Rd Suite 4-PMB 365
Chandler, AZ 85226
Tel: (480) 699-3690
lindley.bark@mscsoftware.com

Alfred Bowles
BRC
9901 IH 10 West, Suite 1000
San Antonio, TX 78230
Tel: (210) 691-0281
Fax: (210) 691-8823
bowlesap@biodynamicresearch.com

Malcolm Braithwaite
Consultant Adviser in Aviation
Medicine
Headquarters Director Army Aviation
Middle Wallop, Hampshire SO 20 8 DY
United Kingdom
01980-674367
malcbrai@aol.com

Fred Brozoski
General Engineer
USAARL
Building 6901
Fort Rucker, AL 36362
Tel: (334) 255-6889
frederick.brozoski@se.amedd.army.mil

Roy Burrows
Flight & Crash Safety Consultant
H Koch & Sons
36 Whittaker's Mill
Williamsburg, VA 23185-5534
Tel: (757) 229-0773
Fax: (757) 229-0127
lburrows@gateway.net

John Crowley
Aircrew Protection Division Director
USAARL
Building 6901
Fort Rucker, AL 36362
Tel: (334) 255-6943
Fax: (334) 255-6937
john.crowley@se.amedd.army.mil

Clifton Dalgard
Bioscience Specialist
USAARL
Building 6901
Fort Rucker, AL 36362
Tel: (334) 255-6898
Fax: (334) 255-6937
clifton.dalgard@se.amedd.army.mil

Stan Desjardins
President Applied Technologies Division
Simula Safety Systems, Inc.
7414 S. Harl Avenue
Tempe, AZ 85283
Tel: (480) 491-6440
Fax: (408) 345-0729
desjardinss@sssi.simula.com

Stefan Duma
University of Virginia
Department of Mechanical, Aerospace, and Nuclear Engineering
1011 Linden Avenue
Charlottesville, VA 22901
Tel: (804) 296-7288
duma@virginia.edu

Don Dutton
Program Manager Applied Technologies Division
Simula Safety Systems, Inc.
7414 S. Harl Avenue
Tempe, AZ 85283
Tel: (480) 491-4486
Fax: (408) 777-2360
dutton@sssi.simula.com

Bob Gansman
Smula Safety Systems
7414 S. Harl Avenue
Tempe, AZ 85283
Tel: (480) 756-4582
gansmanb@sssi.simula.com

Michael Grant
Engineer
Sikorsky Aircraft
6900 Main Street
Stratfort, CT 06497
Tel: (203) 386-5159
Fax: (203) 386-3717
mgrant@sikorsky.com

Anita Grierson
Simula Technologies
10016 South 51st Street
Phoenix, AZ 85044
Tel: (480) 753-2123
grierson@sti.simula.com

Michael J. Happ
Program Manager
H. Koch & Sons Co.
5410 E. La Palma Avenue
Anaheim, CA 92807
Tel: (714) 779-7000x230
Fax: (714) 779-7141
mhapp@hkoch.com

Uwe Hessmer
Engineering Manager
Autoflug GMBH & CO
Industriestr. 10
Rellingen, Germany D-25462
+49-4101-307-260
u.hessmer@autoflug.de

Bob Hood
Aviation Applied Technical Directorate
Bldg. 401
Ft. Eustis, VA 23604-5577
rhood@aatd.eustis.army.mil

Ints Kaleps
Air Force Research Laboratory / HEPA
2800 Q Street
Wright-Patterson, OH 45433-7947
Tel: (937) 255-7486
ints.kaleps@he.wpafb.af.mil

Philip Johnson
Flight Surgeon
USAARL
Building 6901
Fort Rucker, AL 36362
Tel: (334) 255-6815
philip.johnson@se.amedd.army.mil

Horst Kittler
German Ministry of Defense
Postfach 7360 56057 Koblenz, Germany
Tel: GE-(261) 400-7150
Fax: GE-(261) 400-7538
horstgkittler@bwb.org

Mario Maevert
Director of Military Sales
Autoflug GMBH & CO
Industriestr. 10
Rellingen, Germany D-25462
+49-4101-307-250
m.maevert@autoflug.de

Robert Marshall
Application Engineer
TNO-MADYMO
21800 Haggerty Suite 305
Northville, MI 48310
Tel: (248) 449-1755
Fax: (248) 449-7574
marshall@madymo.com

Joseph McEntire
Mechanical Engineer
USAARL
Building 6901
Fort Rucker, AL 36362
Tel: (334) 255-6896
joe.mcentire@se.amedd.army.mil

Thomas Metzler
NAWC – Aircraft Division
Building 2187, Suite 1284
48110 Shaw Road
Patuxent River, MD 20670-1906
1-301-342-9244
metzlertr@navair.navy.mil

Les Neil
CHS F138 Building
Farnborough, Hampshire, UK
GU14 0LX
44(0)1252 394093
lpneil@mail.dera.gov.uk

Joseph Pellettiere
AL/CFBV
2610 Seventh Street
Wright-Patterson AFB 45433-7901
DSN 785-5963
jpellettiere@falcon.al.wpafb.af.mil

William Rockwell
Technical Sales
TNO – Madymo
21800 Haggerty Suite 305
Northville MI 48167
Tel: (248) 449-1755
rockwell@madymo.com

Lowell Roemke
Director of Engineering
BFGoodrich Aerospace, Aircraft
Evacuation System
3420 South 7th Street
Phoenix, Arizone 85040
Tel: (602) 232-4022
Fax: (602) 268-4227
lowell.roemke@aerospace.bfg.com

Ann Schoenbeck
Mechanical Engineer
Naval Air Warfare Center Aircraft Division
Building 2187
48110 Shaw Road Unit 5 Ste 1280
Patuxeut River, MD 20670-1906
Tel: (301) 342-8443
Fax: (301) 342-8503
schoenbeckac@navair.navy.mil

Walter Schrauwen
Senior Development Specialist
MSC Software Corporation
26899 Northwestern Hwy Suite 400
Southfield, MI 48034
Tel: (248) 208-3314
Fax: (248) 208-0915
walter.schrauwen@mscsoftware.com

Michael Schultz
Bldg 1287, Suite 1280
48110 Shaw Road, Unit #5
Patuxent River MD 20670-1906
Tel: (301) 342-8451
Fax: (301) 342-8503
schultzmr@navair.navy.mil

Dennis Shanahan
ARCCA Incorporated
2288 Second Street Pike
Penns Park, PA 18943-0078
Tel: (215) 598-9750
Fax: (215) 598-9751
dshanahan@arcca.com

Steve Soltis
Federal Aviation Administration
3960 Paramount Blvd
Lakewood, CA 90712
Tel: (310) 627-5207
stephen.soltis@faa.dot.gov

George Sprague
Simula Safety Systems
7414 S. Harl Avenue
Tempe, AZ 85283
Tel: (480) 756-4573
Spragueg@sssi.simula.com

Steve Smith
Simula Safety Systems, Inc.
7414 S. Harl Avenue
Tempe, AZ 85283
Tel: (480) 730-4439
Fax: (480) 777-2360
smiths@sssi.simula.com

William Statz
28 Holmbury Avenue
Crowthorne, Berks RG45 GTO
United Kingdom
011-44-(0) 1344-775775

Charles VanDruff
Engineering Manager
H Koch & Sons
5410 E. LaPalma Avenue
Anaheim, CA 92807
Tel: (714) 779-7000
Fax: (714) 779-7141
cvandruff@hkoch.com

Kent Weiter
Program Manager, Aircrew Integrated Systems
CABS Project Engineer
ATTN: SFAE-AV-LSE
Building 5681
Redstone Arsenal, AL 35898
Tel: (256) 313-4280
Fax: (256) 313-4346
wieterk@peoavn.redstone.army.mil

Bob Wildzunas
US Army Safety Center
Bldg 4905 5th Ave
Ft Rucker, Al 36362
Tel: (334) 255-2477
wildzunr@safety-emh1.army.mil

Edward Wissel
Project Manager
Aircrew Integrated Systems
Building 5681, SFAE AV LSE
Redstone Arsenal, AL 35898
256-313-4300
wissele@peoavn.redstone.army.mil

Jin Woodhouse
AMCOM
ATTN: AMSAM-AR-T-V
Building 401
Fort Eustis, VA 23604-5577
Tel: (757) 878-5875
Fax: (757) 878-2543
jwoodhouse@eustis-aatds1.army.mil

Peter Zatezalo
President
H. Koch & Sons
5410 E. La Palma Avenue
Anaheim, CA 92807
1-714-779-7000
Fax: 1-714-779-2983
patezalo@hkoch.com

Richard Zimmerman
Zerad Inc
425 East Greenway Drive
Tempe, AZ 85282-6938
Tel: (480) 456-1010'
zerad@mindspring.com

Schedule

Time	December 1 - Events	December 2 - Events	December 3 - Events
0730-0800	Continental Breakfast	Continental Breakfast	Continental Breakfast
0800-0830	**Administration** - Crowley **Welcome** - Powell	**Modelling and Design I** Design Considerations for Aircraft Crash Sensing - Gansman	**Safety II** Lateral Airbag Deployment and Upper Extremity Injury - Duma
0830-0900	**Keynote Address** Occupant Restraint in Aviation: A Historical and Personal Perspective - Shanahan	An Objective Evaluation Of The Potential For Inadvertent CABS Deployment - Happ	
0900-0930		Vent Control as a Means of Enhancing Airbag Perfomance - Zimmerman	Predicting Airbag-Related Injury Using Anthropometric Test Devices - McEntire
0930-1000	AM Break	AM Break	AM Break
1000-1030	**Applications I** US Army Program Review - Wieter	**Modelling and Design II** Modeling Multi-Airbag Systems for Optimal Protection - Avula	**Effectiveness I** Assessing Airbag Performance : The IAT Approach - Alem
1030-1100	Navy Programs; Airbag Performance & Design Issues For Water Crashes - Schultz	Computer Modeling and Simulation to Assess Inflatable Restraint Safety and Effectivness - Bark	Crash Protection Performance of a Helicopter Cockpit Airbag System - Gansman
1100-1130	Air Force Airbag Projects - Pellettiere	Design of Inflatable Restraints for Crew Seating using MADYMO - TNO	Inflatable Restraint Systems : A UK Miltary Perspective - Neil
1130-1300	Lunch	Lunch	Lunch
1300-1330	**Applications II** Simula's Line of Tubular Inflatable Restraint Technologies - Grierson	US Space and Rocket Center Tour (Optional)	**Effectiveness II** A Retrospective Analysis of Potential Airbag Benefit in US Army Helicopter Crashes - Johnson
1330-1400	The Inflatabelt Occupant Restraint System - Roemke		Crashworthy Factors in British Army Helicopters - Braithwaite
1400-1430	**Safety I** Airbag Related Eye Injuries : The Automotive Experience - Bowles		Projected Airbag Effectiveness in the AH-64 - McEntire
1430-1500	PM Break		
1500-1530	Inadvertent Deployment of Inflatable Occupant Restraints - Sprague		
1530-1600	Effect of Airbag Deployment on Helicopter Flight Control - Brozoski		
1600-1630	In-flight CABS Deployment : A Test Report - Woodhouse		